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CONTENTS

Page 3 : TRANSFORMERS FOR DIRECT ARC STEEL MELTING FURNACES, *by F. A. Smith, Transformer Department, Stafford.*

17 : THE NAPIER MODEL AND PRECISION WORKSHOP.

23 : AN ELECTRIC MOTOR DRIVEN GAS COMPRESSING INSTALLATION OF THE EAST MIDLANDS GAS BOARD, *by A. Ramskill of The English Electric Company, and R. Hutchinson, A.Fuel, M.Inst.Gas E., Divisional Engineer of the East Midlands Gas Board, Leicester and Northants Division.*

26 : DIESEL-ELECTRIC LOCOMOTIVES IN JAMAICA.

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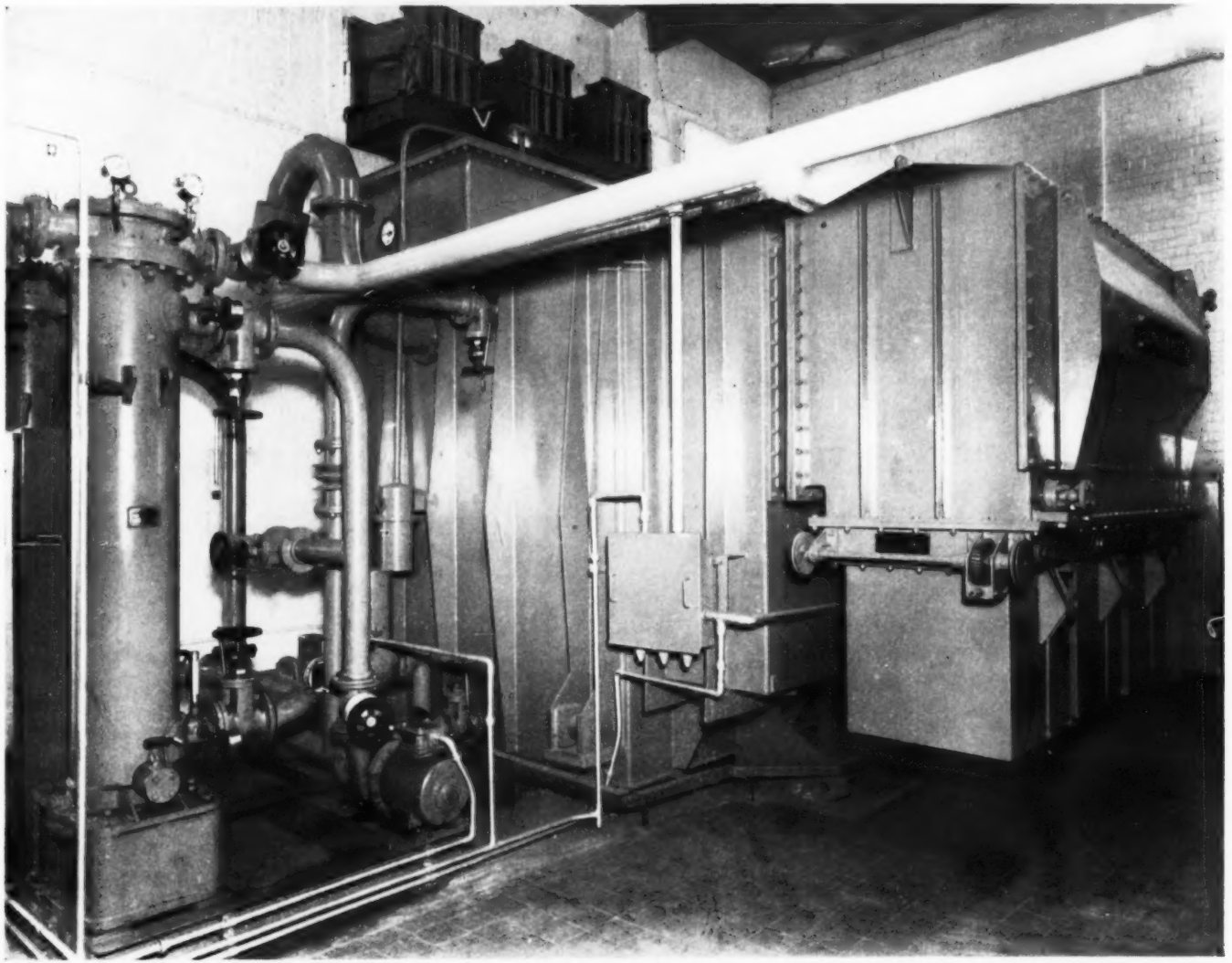


A 20,000 kVA 66,000 volt arc furnace transformer with on-load tap-changing equipment, installed at the works of Samuel Fox Limited, near Sheffield

Transformers for Direct Arc Steel Melting Furnaces

By F. A. SMITH, Transformer Department, Stafford.

IN MANY INDUSTRIAL PROCESSES where a concentrated source of heat is required, electricity is frequently the ideal medium. One example is the production of high grade steel in a direct-arc melting furnace.

Of the many attractions which these furnaces offer to the steelmaker, probably the most important is the comparative ease with which special alloy steels can be produced, and it is for this purpose that the majority of such furnaces have been installed.

The demand for these steels has been steadily increasing year by year, particularly since the end of World War II, and it is not surprising therefore that there has been a correspondingly increased demand for the direct-arc steel melting furnace.

The demand for this type of furnace has been further increased by economical considerations, the capital cost of the open hearth furnace being high, coupled with the continually rising costs of suitable fuels.

The manufacturers of both the furnaces and the associated electrical equipment have done, and are doing, everything possible to reduce the cost per ton of steel produced in the electric furnace.

One of the ways in which this has been accomplished is by a very considerable increase in the tonnage capacity of the furnaces. However, the extent to which this was possible was entirely dependent upon the ability of the transformer and switchgear manufacturers to produce electrical equipment of a similarly increased size. In this The English Electric Company has played the leading part, being the first to meet the demand for the very large arc furnace transformers required, and towards the end of 1953 introducing on-load tap-changing equipment to such transformers for the first time.

In addition to permitting a finer degree of control of the furnace, the provision of on-load tap-changing equipment on the transformer itself contributes to the reduction in the cost per ton of steel produced, since on installations where it is employed there is no interruption of the heat input to the furnace during adjustment of the electrode voltage.

With on-load tap-changing equipment it is of course unnecessary to open the controlling circuit-breaker each time the voltage to the furnace is adjusted. Consequently, not only is the frequency of operation of the main circuit-breaker, and therefore its maintenance, drastically reduced, but of far greater importance, the operation of very large furnaces direct from incoming supplies as high as 66,000 volts has been made possible.

There is therefore virtually no upper limit, so far as transformers and switchgear are concerned, to the size of the direct-arc steel melting furnace which can be produced to-day. An 80 ton furnace, powered by an 'English Electric' 66,000 volt 20,000 kVA transformer, has recently been commissioned, and even larger sizes are being considered.

Obviously, the addition to the existing load of a steelworks of furnaces requiring this amount of power in most cases necessitates the provision of a supplementary supply from the local electricity undertaking, and this supply is most likely to be given at either 33,000 or 66,000 volts. Due to the fluctuating load of the furnace during the melting cycle, this is particularly desirable for two reasons : firstly, the risk of interference with other consumers' supplies in the form of voltage variation must be avoided, and secondly, good voltage regulation of the supply to the furnace is highly advantageous. To this latter end it is usually accepted to-day that the fault level of the supply to the furnace should be at least ten times that of the load taken by the furnace.

Samuel Fox Limited, near Sheffield

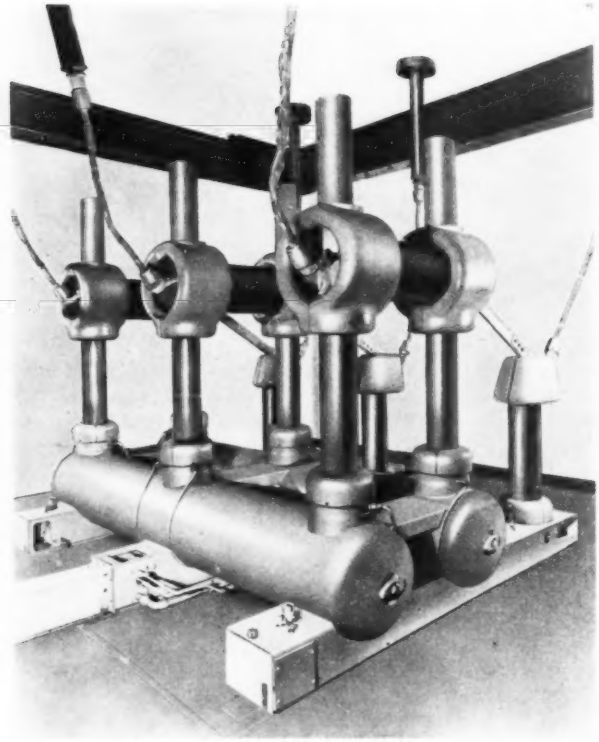


Fig. 1.—The 66,000 volt 1,500 MVA air-blast circuit-breaker controlling the arc furnace transformer shown in the frontispiece

Due to the high fault level of 33,000 and 66,000 volt supplies, switchgear having a correspondingly high breaking capacity has to be employed, but, except when operating a direct-arc steel melting furnace, it is not usually required to withstand very frequent operation.

Although 'English Electric' air-blast circuit-breakers are fully capable of the frequent operation required by arc furnace installations employing off-circuit tap-changing equipment at voltages up to a maximum of 33,000, no 66,000 volt switchgear is available to withstand the number of operations involved when off-circuit tap-changing is employed.

However, with on-load tap-changing equipment, the number of circuit-breaker operations is reduced to something of the order of 5,000 per year, and the 'English Electric' 66,000 volt 1,500 MVA air-blast circuit-breaker is capable of this duty.

Typical Installations

A large high-voltage installation incorporating an 'English Electric' transformer and switchgear was commissioned in 1957 at the Stocksbridge Works of Samuel Fox Limited, near Sheffield, with a Birlec furnace having a capacity of 80 tons. It is powered by a 20,000 kVA 66,000 volt arc furnace transformer having on-load tap-changing equipment, and is switched at 66,000 volts by means of an air-blast circuit-breaker. The transformer and circuit-breaker appear in the frontispiece and Fig. 1 respectively. This is the largest arc furnace transformer, and the second with on-load tap-changing equipment, to be manufactured and installed in the United Kingdom.

The first installation of its kind was commissioned in November 1953 at the same works of Samuel Fox Limited. This furnace, having a capacity of 60 tons, was also manufactured by Birlec, and The English Electric Company supplied the transformer and oil circuit-breaker. The transformer is rated at 15,000 KVA and tap-changing is on-load. The equipment operates at 11,000 volts.

Othes large furnaces employing 'English Electric' transformers and switchgear include one of 65 tons capacity installed by the Electric Furnace Company in 1957 at the works of the South African Iron and Steel Corporation near Johannesburg. The transformer, which has on-load tap-changing equipment, is rated at 15,000 kVA, operates direct from a 33,000 volt supply and is controlled by means of air-blast circuit-breakers.

Two further 20,000 kVA 33,000 volt arc furnace transformers have recently been completed to operate two 80 ton Birlec furnaces which are being installed near Wolverhampton, and three similar 33,000 volt transformers, each rated at 12,500 kVA, together with controlling air-blast circuit-breakers, are nearing completion and are destined to supply Birlec furnaces in Wales. All these transformers have on-load tap-changing equipment.

Arc Furnace Transformer Duty

When supplying a direct-arc steel melting furnace,

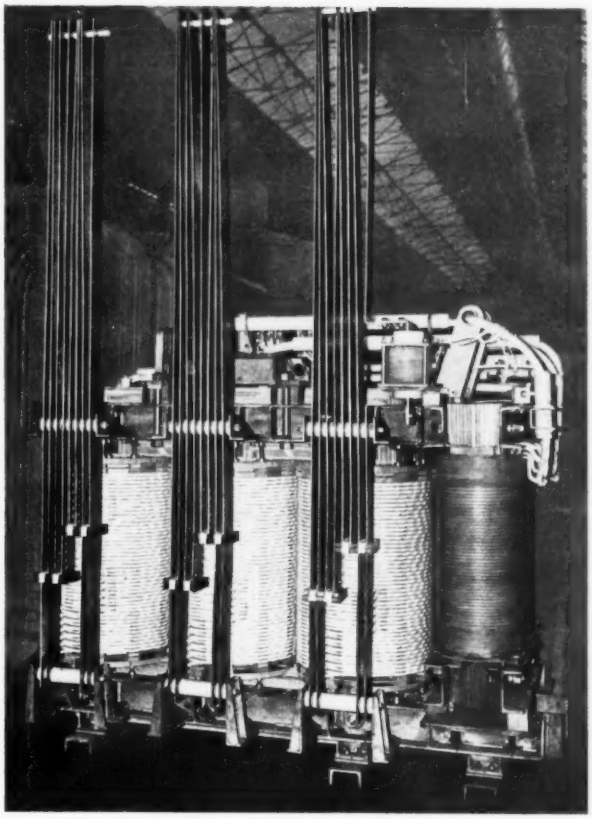


Fig. 2.—Low voltage side of 2,500 kVA 11,000 volt arc furnace transformer with off-circuit tap-changing equipment

the electrical equipment, and particularly the transformer, has to stand up to a duty which is far more arduous and exacting than that encountered in any other application. In addition to providing the furnace with currents of many thousands of amperes over a very wide range of voltage, the transformer must also be capable of withstanding the very severe overloading which occurs during the melting period. During this period the furnace electrodes tend to tunnel into the charge and inevitably, as this proceeds, loose metal falls in from above and the electrodes are short-circuited. In order to limit the resulting short-circuit current to a reasonable value—usually between 2½ and 3 times full load—the overall reactance of the installation is in most cases fixed between 30 and 40%. When this value of reactance is not inherent in the installation, supplementary reactance is provided in the form of a tapped reactor, mounted in the transformer tank.

In addition to fulfilling these requirements, the furnace transformer must be of unquestionable reliability, since no alternative supply is available to the furnace in the event of breakdown.

Broadly speaking, arc furnace transformers may be divided into two categories, the first of which embraces transformers up to about 10,000 kVA for connection to supply voltages up to about 11,000. On these transformers, off-circuit tap-changing equipment is most usually fitted. Transformers having a rating in excess of 10,000 kVA come within the second category and are usually designed to operate from supply voltages between 11,000 and 66,000. On these transformers on-load tap-changing equipment is almost invariably fitted. Obviously there are exceptions, and 'English Electric' arc furnace transformers as small as 2,500 kVA with on-load tap-changing equipment have recently been manufactured.

Design Considerations

The problems involved in providing on-load tap-changing equipment on very large arc furnace transformers will more readily be appreciated if the design of the smaller units incorporating off-circuit tap-changing equipment is first examined. The core and windings of a typical small transformer are shown in Figs. 2 and 3.

It will be seen that the L.V. windings are mounted on the outside of the coil stack and that these consist of a number of individual disc coils which are connected in groups in parallel to the vertical copper busbar assembly.

The high voltage primary windings are positioned between the low voltage windings and the core. Tappings are brought out from these windings in order that variation of the secondary voltage may be obtained.

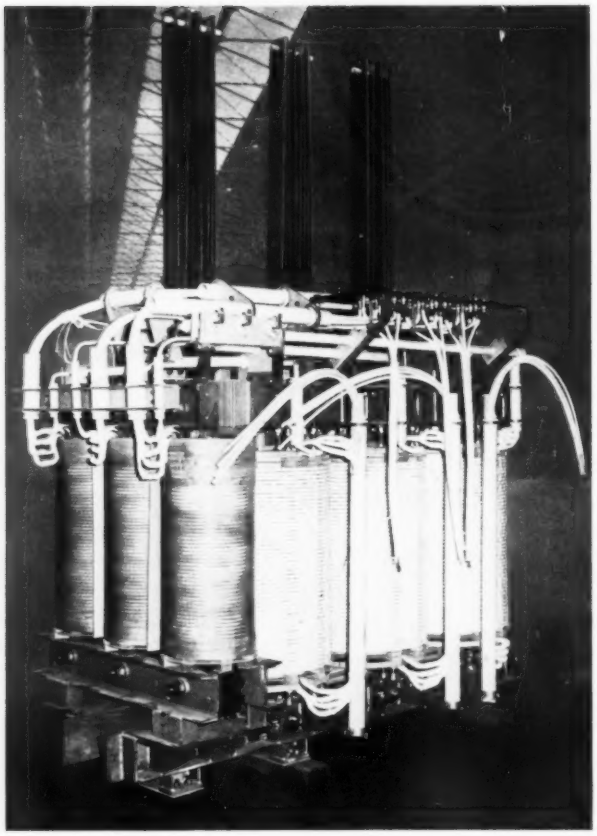


Fig. 3.
High voltage side of the 2,500 *kVA* 11,000 *volt arc furnace transformer in Fig.* 2, *showing inbuilt reactor and tapping connections*

In order to minimise the number of tappings on the transformer primary windings and thereby detract as little as possible from the mechanical strength of these windings, all six phase-ends are brought out to enable the windings to be connected in either delta or star. By this means, the number of tappings required on the windings is only half the number of secondary voltages available. Also, the amount of over-winding necessary to produce the desired variation in secondary voltage is reduced, minimising the voltage which appears across the tapping switch and appreciably reducing the overall size of the transformer.

The delta-star re-connection of the primary windings is carried out automatically by the motorised off-circuit tap-changing equipment.

As the inherent reactance of a furnace installation of this size—2,500 kVA—is insufficient to limit the short-circuit current to a reasonable value during the melting period, additional reactance is provided in the form of a tapped reactor which can be seen in the illustration mounted on an extension of the core clamping frames.

The tapping leads from both the reactor windings and the transformer primary windings with which they are connected in series, are terminated at the link board shown in Fig. 4.

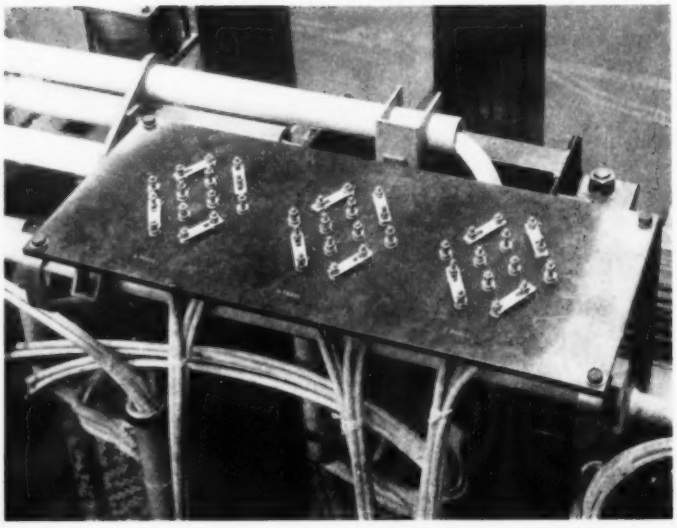


Fig. 4.—*Reactor link board fitted to the* 2,500 *kVA* 11,000 *volt arc furnace transformer shown in Figs.* 2 *and* 3

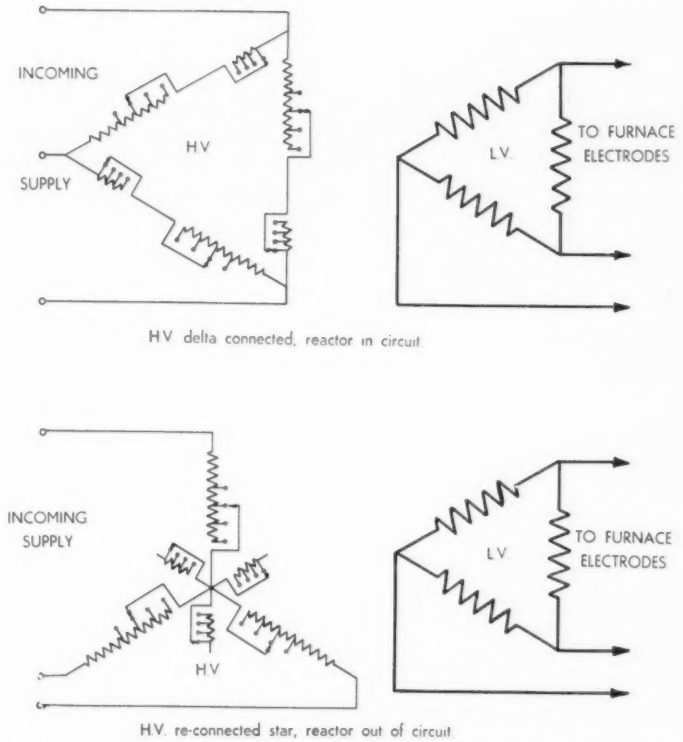


Fig. 5.—Typical winding connections of an arc furnace transformer with off-circuit tap-changing equipment, employing delta-star primary re-connection

automatically switched out of circuit by the off-circuit tap-changing equipment when the primary windings are connected in star.

The winding connections of a transformer of this type are shown diagrammatically in Fig. 5.

On arc furnace transformers falling within the second category —those employing on-load tap-changing equipment—it is not possible to take advantage of the delta-star re-connection of the primary windings, since it is impossible to accomplish this when the transformer is energised. Consequently, if a tapped primary winding were used for a transformer with on-load tap-changing equipment, it would be necessary to provide sufficient tappings on the primary winding to cover the whole range of secondary voltage variation required.

Bearing in mind that large furnace transformers almost invariably operate from 33,000 volt or even higher voltage supplies, it

At this link board, which is mounted below oil level and accessible via hand-holes in the transformer tank cover, it is possible to pre-select any available value of reactance to be in circuit with any secondary voltage.

Since additional reactance is not usually necessary at the lower end of the voltage range, the reactor is

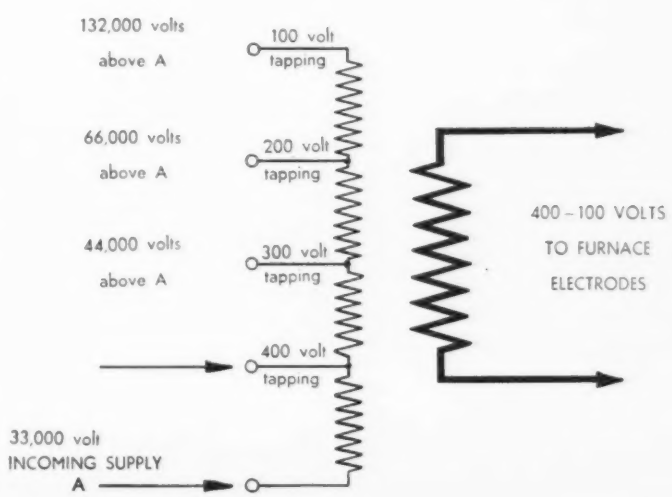


Fig. 6.
Diagram illustrating the occurrence of high induced voltage in the over-winding of a transformer having H.V. tappings for L.V. variation

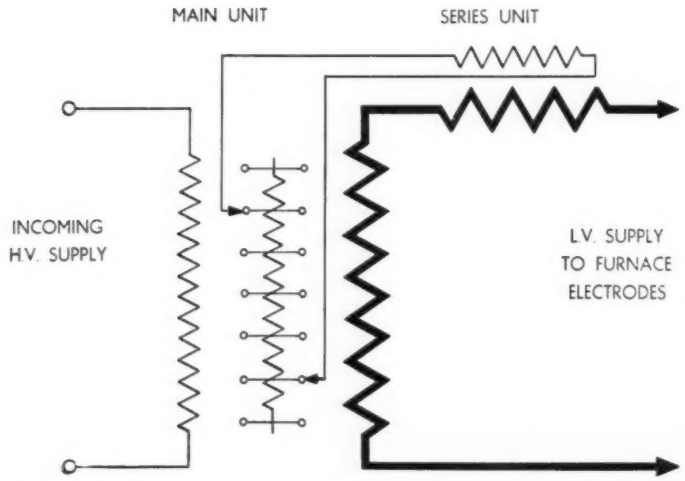


Fig. 7.—Circuit diagram of one phase of large arc furnace transformer employing ' series booster ' construction

will be seen that with the transformer connected to give maximum secondary voltage, due to the auto-transformer effect of the tapped primary winding, a voltage would be induced in the over-winding amounting to several times that of the supply voltage. Further, this induced voltage would appear across the selector-switch portion of the on-load tap-changing equipment.

Reference to Fig. 6 will show that within a transformer operating from a 33,000 volt supply and having a typical secondary voltage range of 400 to 100, the voltage induced in the over-winding and appearing across the tapping switch on the 400 volt tapping would be 99,000 volts, the voltage across the whole primary winding being 132,000 volts.

Obviously such voltages are most undesirable within a transformer connected to a 33,000 volt supply, and The English Electric Company therefore adopted a design in which unduly high induced voltages would not be encountered.

Two alternative forms of construction are possible, one using a series booster and the other a voltage regulator. These are shown diagrammatically in Figs. 7 and 8, and for the sake of simplicity are illustrated as single-phase units, although in actual fact they would most probably be three-phase. As will be seen from the diagrams, both forms of construction employ two component transformers which are mounted together in one common tank.

In the series booster construction, the secondary windings of both transformers are connected in series, and both therefore have to carry the very heavy current at low voltage which is supplied to the furnace. The main transformer carries a third winding which is tapped and which supplies the primary windings of the booster transformer via the on-load tap-changing equipment.

With the voltage regulator construction, a voltage regulating transformer is connected directly across the incoming supply, and the output from this transformer is fed directly into the primary windings of the main step-down transformer, the secondary windings of which supply the heavy current at low voltage to the furnace. Tappings are incorporated on the voltage regulating transformer to which the on-load tap-changing equipment is connected. The main step-down transformer is entirely without tappings.

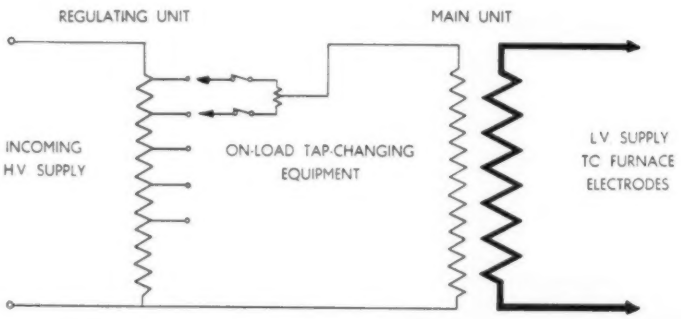


Fig. 8.—Circuit diagram of one phase of large arc furnace transformer employing ' voltage regulator ' construction

It will be apparent that the main difference between the two designs is constructional, in that whereas the series booster design necessitates two heavy current windings which have to be connected in series within the tank, the voltage regulator design requires only one such heavy current winding.

In order to prevent unwanted reactance, unduly high stray losses and local overheating, it is essential that all heavy current connections from the low voltage windings are brought out in a highly efficiently interleaved manner. With the voltage regulator design this is a simple matter, as only one low voltage winding is involved, whereas with the series booster construction there is the additional requirement of connecting the two heavy current windings in series within the tank, as well as bringing them out of the tank.

This point will be more readily appreciated by reference to Fig. 9, which shows the low voltage terminations from the main unit of an arc furnace transformer using the voltage regulator construction. A typical voltage regulating transformer is shown in Fig. 10.

The voltage regulator construction has been adopted by The English Electric Company and has been used for all the large transformers to which reference was made earlier in this article.

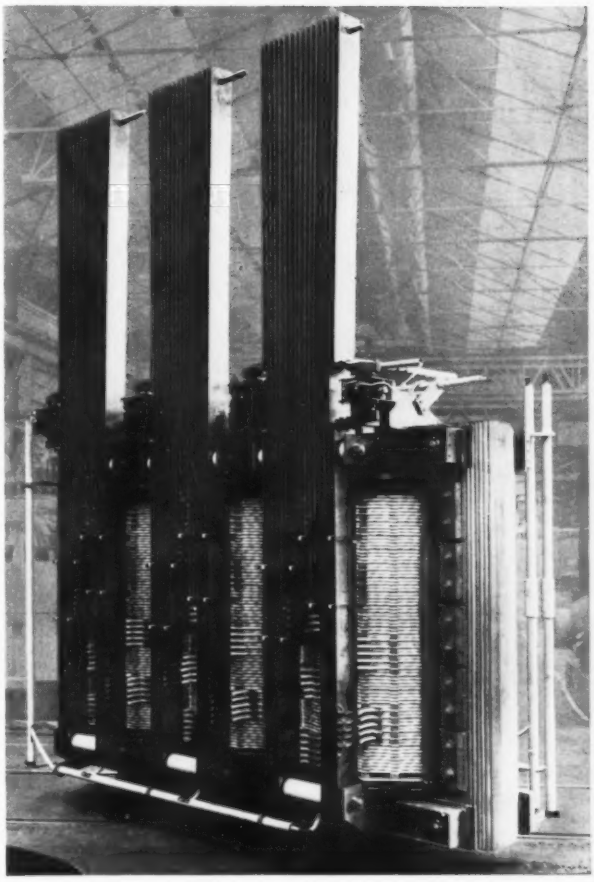


Fig. 9.—Low voltage side of main unit of 20,000 *kVA* 66,000 *volt arc furnace transformer employing ' voltage regulator ' construction*

In addition to the straightforward manner in which it is possible to bring out the heavy current interconnections, there are no internal heavy current connections which might become overheated during service. Further, with the voltage regulator construction, the two component transformers require a total of only three windings, compared with the five required by the series booster. The absence of tappings on the transformer connected directly to the furnace is also an advantage, since it ensures the maximum possible mechanical strength of the windings.

On-load Tap-changing Equipment

Two basically different types of on-load tap-changing equipment are available, either of which may be fitted to the transformer ; one employs reactor transition and the other resistor transition. Both types of equipment have been fitted to ' English Electric ' arc furnace transformers, but in the majority of cases reactor transition has been preferred. The choice of the type of on-load tap-changing equipment to be fitted to a particular arc furnace transformer is left entirely to the purchaser. In deciding this important point, however, a number of facts should be taken into consideration.

For example, a 60 ton arc furnace installation making three melts a day, six days a week, produces

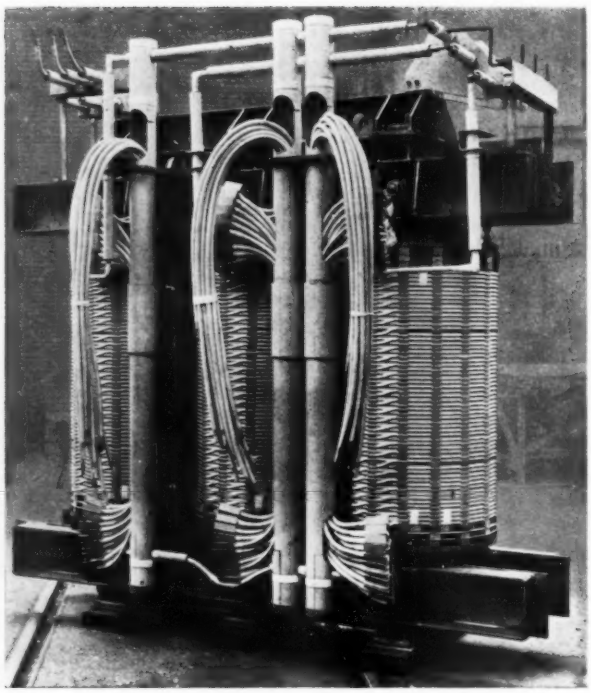


Fig. 10.—Regulating unit of 20,000 kVA 33,000 volt arc furnace transformer employing 'voltage regulator' construction, showing tapping leads for connection to on-load tap-changing equipment

approximately 50,000 tons of steel in a year, which at £100 per ton represents a marketable value of roughly £5 million. At the same time it must be remembered that the continued operation of the furnace is entirely dependent upon the electrical equipment with which it is associated.

Reliability of the electrical equipment is therefore of the highest importance, and anything which can be done to increase it must be regarded as an investment. Similarly, maintenance of the equipment after it has been installed must not be regarded as a nuisance but as an insurance, for by comparison with the possible loss of one week's output of steel from the furnace in question—worth around £100,000—the cost of maintenance is negligible.

On-load tap-changing equipment, when operating on an arc furnace transformer, will in all probability be called upon to perform in excess of 100,000 operations a year. It must also be capable of standing up to the frequent overloading which occurs due to fall-in during the melting period.

Reactor Type

Reactor type on-load tap-changing

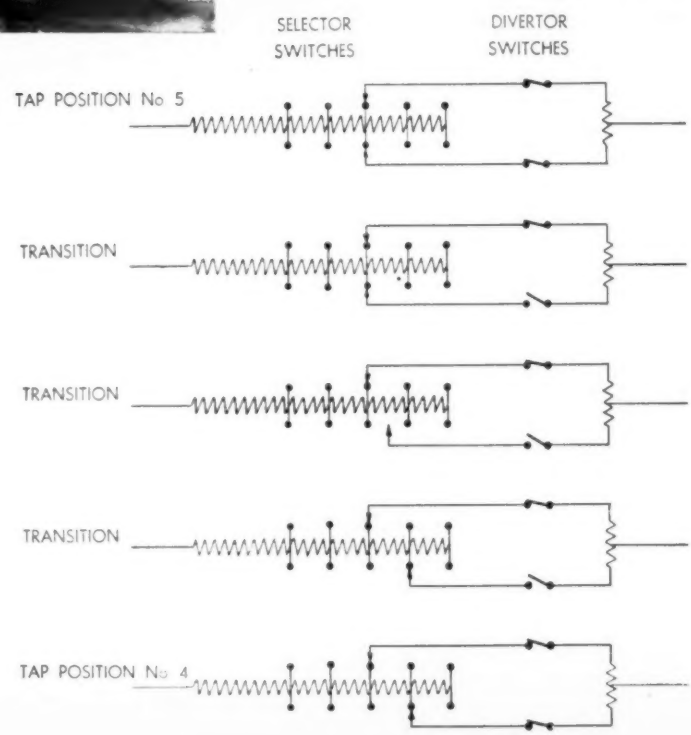


Fig. 11.—Diagram of connections and operating sequence for one phase of reactor type on-load tap-changing equipment

equipment is shown diagrammatically in Fig. 11, from which it will be seen that a centre-tapped autotransformer is employed during the transition period. This autotransformer is continuously rated and the centre tap is also used to provide additional voltages intermediate to those available from the tappings on the transformer windings. Thus, with this type of equipment, the number of tappings required on the transformer windings is only half the number of voltages required.

The maintenance requirements of reactor type on-load tap-changing equipment are not unreasonable. Based on information obtained over a period of years from a typical large arc furnace installation in Britain, it is apparent that the divertor switch contacts are not likely to require attention until approximately 50,000 operations have been completed.

Re-conditioning of the oil in the divertor switch tanks does not appear to become necessary until approximately 15,000 operations have been completed.

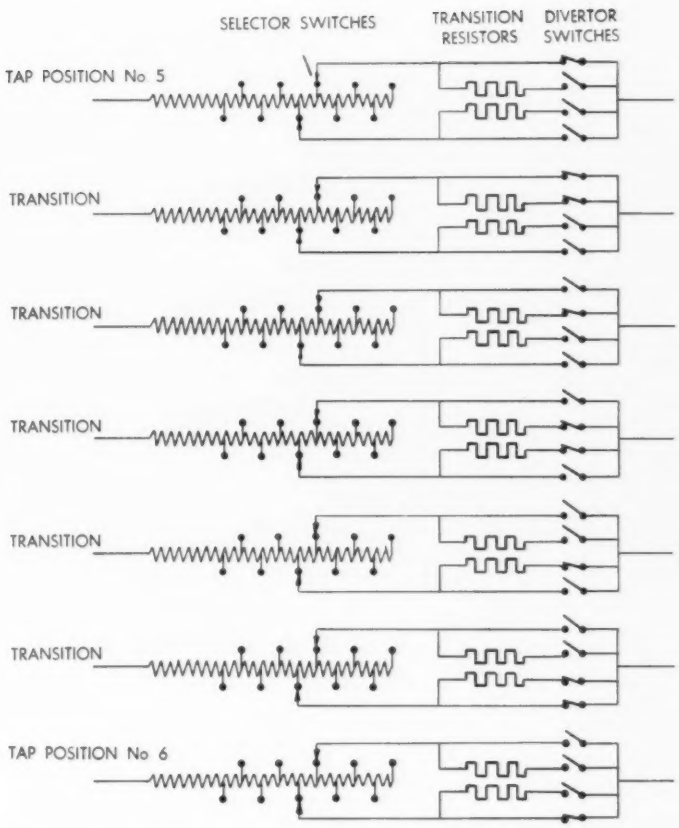


Fig. 12.—Diagram of connections and operating sequence for one phase of resistor type on-load tap-changing equipment

The intervals between necessary maintenance may be judged from the fact that on the arc furnace installation just referred to, the on-load tap-changing equipment completes, on an average, between 2,000 and 2,500 operations in a normal working week.

When undertaken by two good maintenance men, all three divertor switch tanks on this equipment may be lowered, drained, cleaned out and re-filled with fresh oil, the divertor switch contacts and flexible braids renewed, the springs replaced and tensioned, the supporting insulators washed down and the equipment made ready for operation again in a period of two hours.

Resistor Type

The alternative type of on-load tap-changing equipment, utilising resistor transition, is shown diagrammatically in Fig. 12, from which it will be seen that the load current is diverted through two resistors during the tap-changing cycle. Since these resistors are only short-time rated, it is necessary that the tap-change cycle, once initiated, shall be completed without interruption and in the minimum time. The driving mechanism therefore takes the form of a stored energy device. Completion of the tap-changing cycle is thereby assured, even in the event of failure of the auxiliary supply to the driving motor.

It is not possible to state with accuracy what maintenance this type of equipment will require, since no large arc furnace installation has yet been commissioned in Britain on which resistor

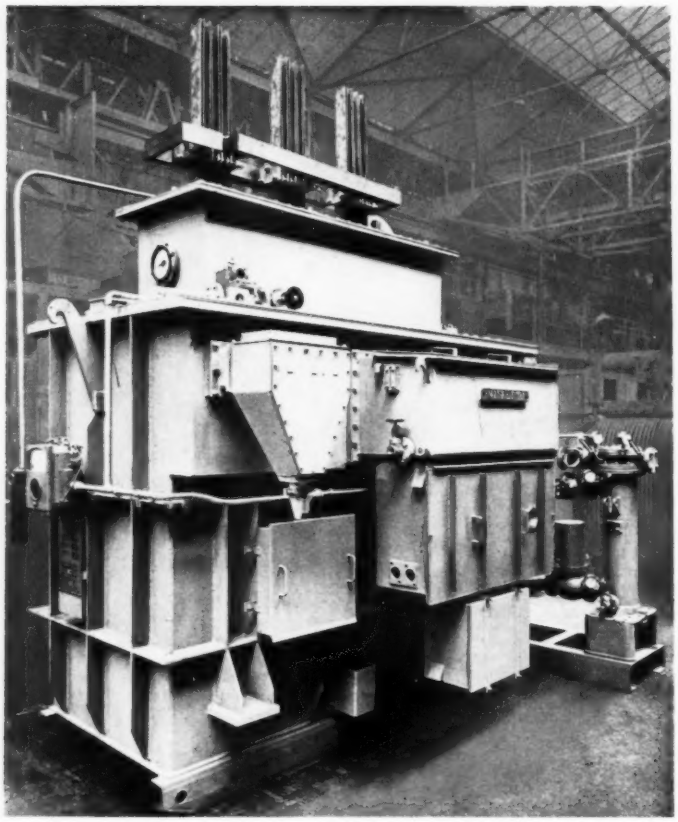


Fig. 13.
Completed 2,500 *kVA* 11,000 *volt arc furnace transformer with off-circuit tap-changing equipment*

The number of tappings required on the transformer windings is only half the number of output voltages required.

With resistor-type equipment, the maintenance requirements may be somewhat less than those of reactor gear. Part of the equipment is short-time rated and adequate safeguards must be incorporated to ensure reliable operation. A stored energy device is necessary between the driving motor and the tap-changing equipment. The number of tappings required from the transformer windings is twice that with reactor gear.

type on-load tap-changing equipment has been employed.

Summary

Briefly, the two alternative types of tap-changing equipment available may be summarised as follows.

Reactor-type equipment is continuously rated and therefore is not endangered by failure of the operating mechanism. The operating mechanism is called upon to transmit a steady drive to the moving parts within the switch, and mechanical wear and tear are therefore a minimum. The maintenance requirements are not unreasonable.

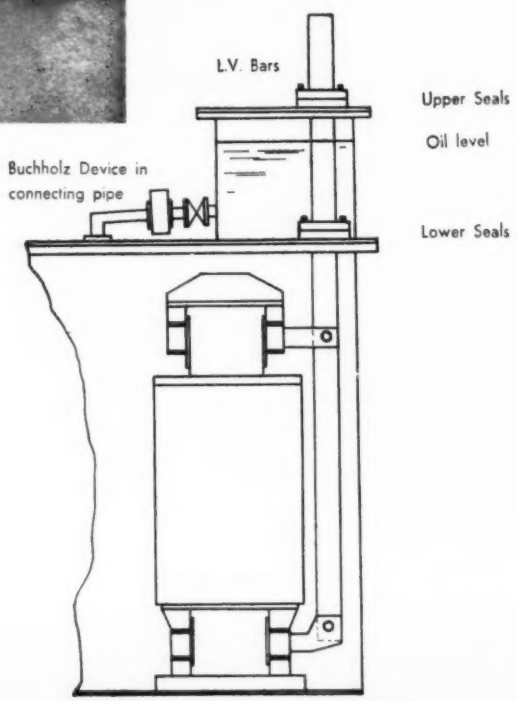


Fig. 14.—'*English Electric*' *leak-proof method of bringing out heavy current L.V. connections via oil conservator*

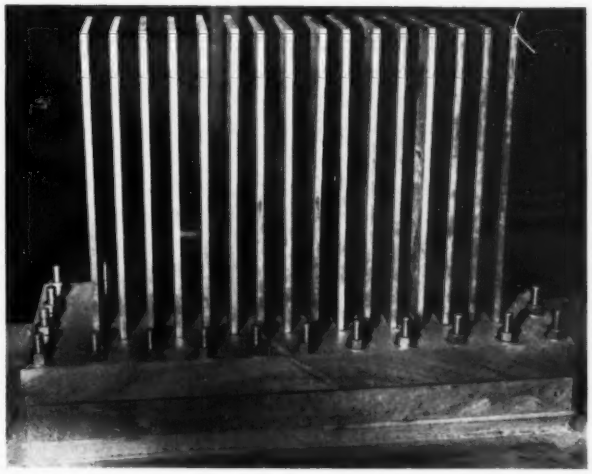


Fig. 15.—Sealing bushes around L.V. bars on cover plate of oil conservator

It is significant that of ten 'English Electric' arc furnace transformers supplied in various sizes up to 20,000 kVA, seven, including the largest, incorporated reactor-type on-load tap-changing equipment.

Amongst the seven transformers with reactor-type equipment was the second unit, of 20,000 kVA, already mentioned as supplied to Samuel Fox Limited. The original 15,000 kVA transformer which was commissioned at that Company's works in 1953 was also fitted with reactor type tap-changing equipment, and this has now completed nearly half a million trouble-free operations.

Reactance

On large arc furnace installations requiring an electrical input above about 10,000 kVA, the reactance external to the transformer and inherent in the low voltage busbars and flexible cables connecting the transformer to the furnace, together with that in the electrode arms and the electrodes themselves, is found to be sufficient, when added to the reactance of the transformer, to limit the overcurrent to a reasonable value—not more than three times full load current—when fall-in occurs during the melting period. Consequently, the supplementary reactor provided in the smaller arc furnace transformers is normally not necessary, but can be incorporated if required for some special process.

As a guide, the reactance at maximum secondary voltage of arc furnace transformers in the 10,000-50,000 kVA range may be taken as from eight to twelve per cent according to size.

Large Transformer Construction

It will be seen from the frontispiece and Fig. 13 that the construction introduced and used so successfully by The English Electric Company throughout the smaller range of arc furnace transformers, has been retained on the very large units being produced to-day.

The most important feature is the completely leak-proof manner in which the very heavy current

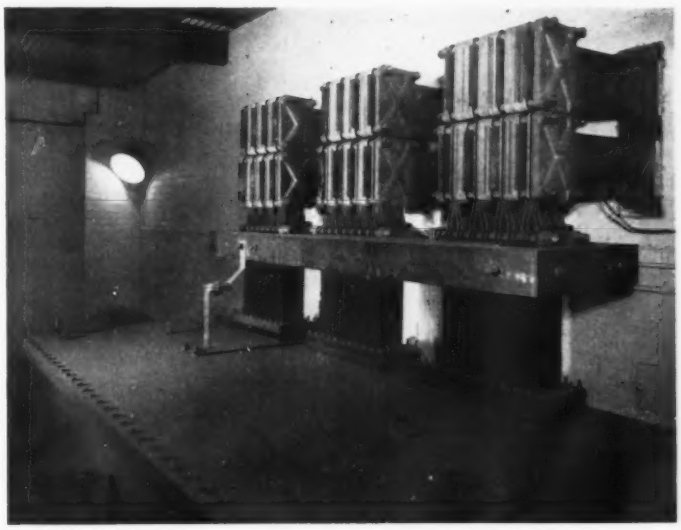


Fig. 16.—Low voltage delta connections on 20,000 kVA 66,000 volt arc furnace transformer

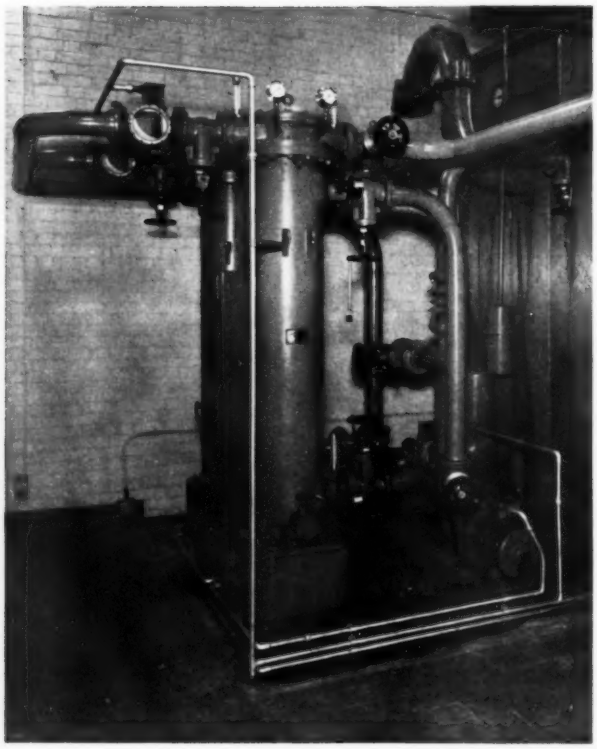


Fig. 17.—Duplicate oil coolers fitted to 20,000 kVA OFW arc furnace transformer

connections from the low voltage windings are brought out of the tank. To accomplish this the oil conservator is made an integral part of the tank cover, and the vertical copper bars which can be seen in Fig. 9, carrying the heavy current from the low voltage windings, are brought out through the oil conservator. This is shown in detail in Fig. 14, from which it will be seen that sealing bushes are provided in both the bottom and the top plate of the conservator. The function of these bushes is not to prevent oil leakage but, in the case of the upper bushes (Fig. 15), to seal the air within the oil conservator from the outside atmosphere in order to ensure that the transformer breathes only through the silica gel de-hydrating breather. To maintain the oil within the conservator separate from that in the main tank, a second set of seals is provided in the base of the conservator. By this means, the exchange of oil between the oil conservator and the main tank during temperature changes is directed through the connecting pipe in which the Buchholz device is fitted.

As previously stated, all ends of the low voltage windings are brought out and the delta connection made externally. The form which the delta connection takes may be seen from Fig. 16.

In cases where the height within the transformer house is limited, the oil conservator is constructed from non-magnetic metal in order that the delta connections may be made in close proximity to the conservator cover without any risk of this becoming overheated by induction.

Protection of the transformer is afforded by a double-float Buchholz device and also by one or more winding temperature indicators fitted with alarm and tripping contacts. To ensure that these instruments give as true an indication as possible of the temperature conditions within the windings, the reference current is obtained from current transformers connected into the low voltage circuit. Such current transformers can be seen in Fig. 9, together with similar units for use with the electrode control gear. Further protection is afforded, for forced cooled transformers, by flow relays in the oil and water circuits.

Cooling

In the majority of cases arc furnace transformers are water cooled, since this system is compact and requires relatively little floor area in a situation where this is usually at a premium. Nevertheless, on a number of occasions both natural and forced air cooling have been employed on the smaller range of transformers. These forms of cooling, however, suffer from the disadvantage that, as the cooling air available in a steelworks is frequently dirty, filters often have to be installed to prevent the oil radiators becoming clogged.

On the larger arc furnace transformers, where water cooling is used, duplicate coolers are usually provided, each capable of dissipating the full-load transformer losses. A typical installation is shown

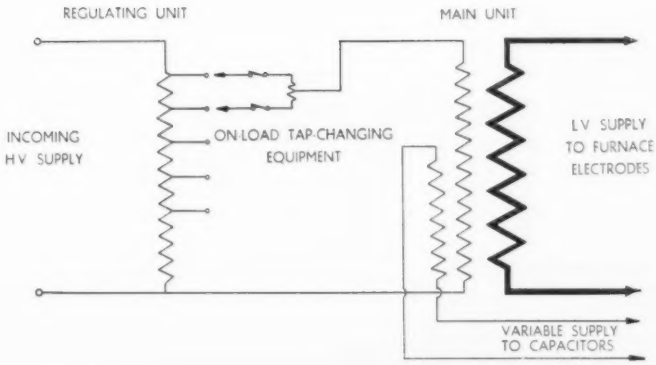


Fig. 18.—*Circuit diagram for one phase of large arc furnace transformer employing 'voltage regulator' construction and incorporating tertiary windings for semi-automatic power factor correction*

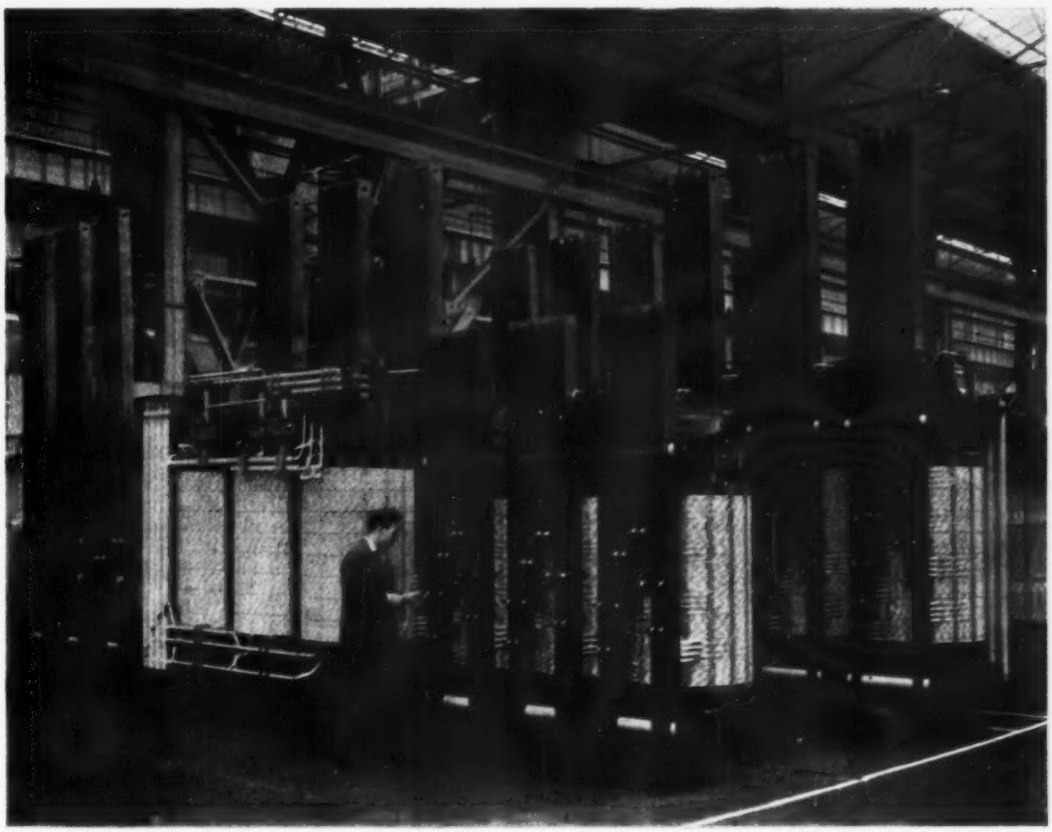


Fig. 19.—*A group of arc furnace transformers under construction totalling* 87,500 *kVA and ranging in size from* 10,000 *to* 20,000 *kVA*

in Fig. 17. The oil-water heat exchangers are easily maintained, it being possible to clean out the water circuit without disturbing any pipework. Submersible-type oil circulating pump-motor units are employed which are glandless and leakproof. In the illustration shown, the cooler control gear, including the circulating pump motor starters, is housed in a cubicle.

Power Factor Correction

For various reasons it is sometimes desirable that an arc furnace installation shall operate at as high a power factor as possible.

On the smaller installations this is attained by connecting a capacitor bank across the incoming supply to the transformer.

On the larger installations, where double-unit voltage regulator construction is employed on the transformer, a form of semi-automatic power factor correction is possible. This is achieved by incorporating a third winding on the main step-down transformer, to which a capacitor bank of the desired size is connected. This is shown diagrammatically in Fig. 18. Since the voltage from the tertiary winding varies in direct proportion to that being supplied to the furnace electrodes, the effective value of capacitance in circuit is progressively reduced as the input to the furnace is decreased, with the result that there is no risk of over-correction at low load.

This method of power factor correction has the additional advantage that even though a transformer may be operating from a 33,000 or 66,000 volt supply, the most economical voltage may be chosen to operate the capacitors. In most cases this is found to be 11,000 volts.

Switchgear

Switchgear for use with an arc furnace transformer must be very carefully selected, since it must be capable of a frequency of operation far in excess of that encountered on a distribution system. Even when on-load tap-changing equipment is fitted to the transformer, somewhere in the region of 5,000 circuit-breaker operations will be made during a year's service. With off-circuit tap-changing, a considerably higher number of operations may be recorded in the same period.

Air-blast switchgear is ideally suited to this duty, since the lightness of the moving parts ensures mechanical reliability and renders such equipment inherently capable of a large number of operations without attention. The maintenance required is extremely small and can be carried out quickly due to the simplicity of operation and the accessibility of all parts.

'English Electric' air-blast circuit-breakers are in service on various arc furnace installations operating at up to and including 66,000 volts, and many of these have been in commission for a considerable number of years. These breakers are available to control installations operating at supply voltages up to 33,000, irrespective of whether off-circuit or on-load tap-changing equipment is incorporated on the transformer, and up to 66,000 volts when on-load tap-changing equipment is provided, thus reducing the number of circuit-breaker operations to no more than 5,000 a year.

Conclusion

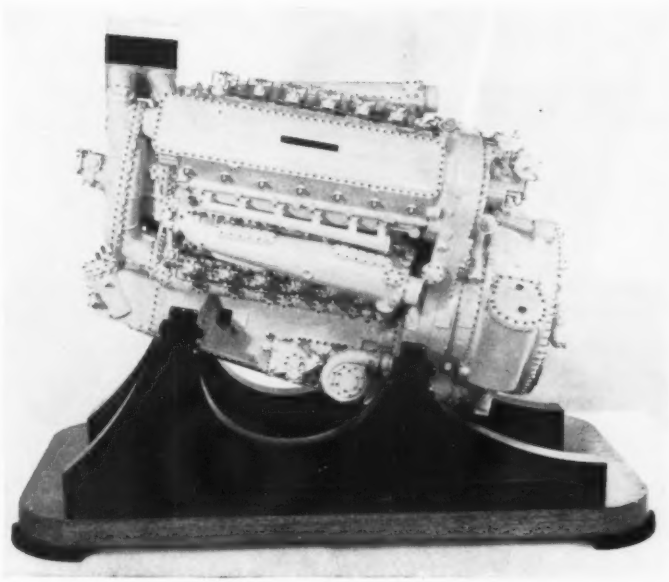
The demand for the direct-arc steel melting furnace is expected to increase steadily, and much of this demand will be for furnaces having even larger capacities than those in operation to-day.

The English Electric Company has already completed designs for arc furnace transformers as large as 50,000 kVA and for operation at 66,000 volts, and the possibility of operating such equipment from the 132,000 volt National Grid is being examined.

The Napier Model and Precision Workshop

THE REPRODUCTION IN MINIATURE of familiar objects has been an absorbing hobby and source of relaxation for centuries, but in industry model making can become a very serious business.

Models are used by many of Britain's major engineering concerns as a means of showing their products overseas. The precision engineering products of D. Napier & Son Limited, including aero engines, helicopter power units and diesel engines, are difficult to show in their complete range at many of the international exhibitions and overseas trade fairs, due to the size of the larger engines and the limited space available,



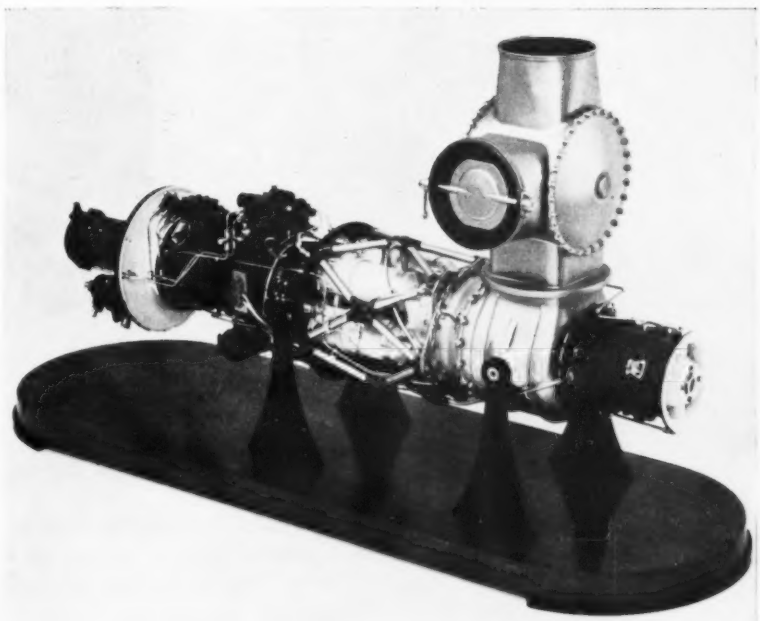
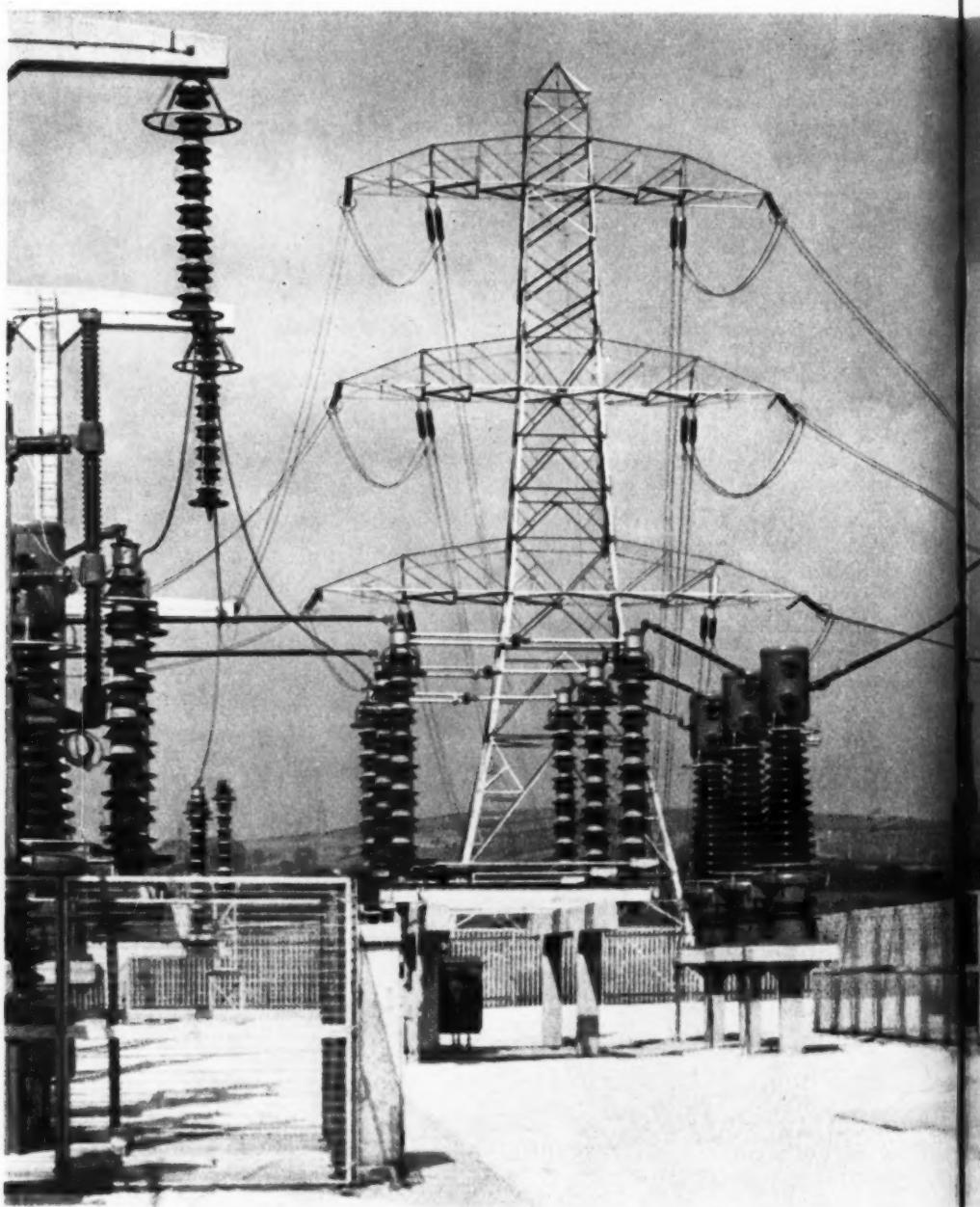


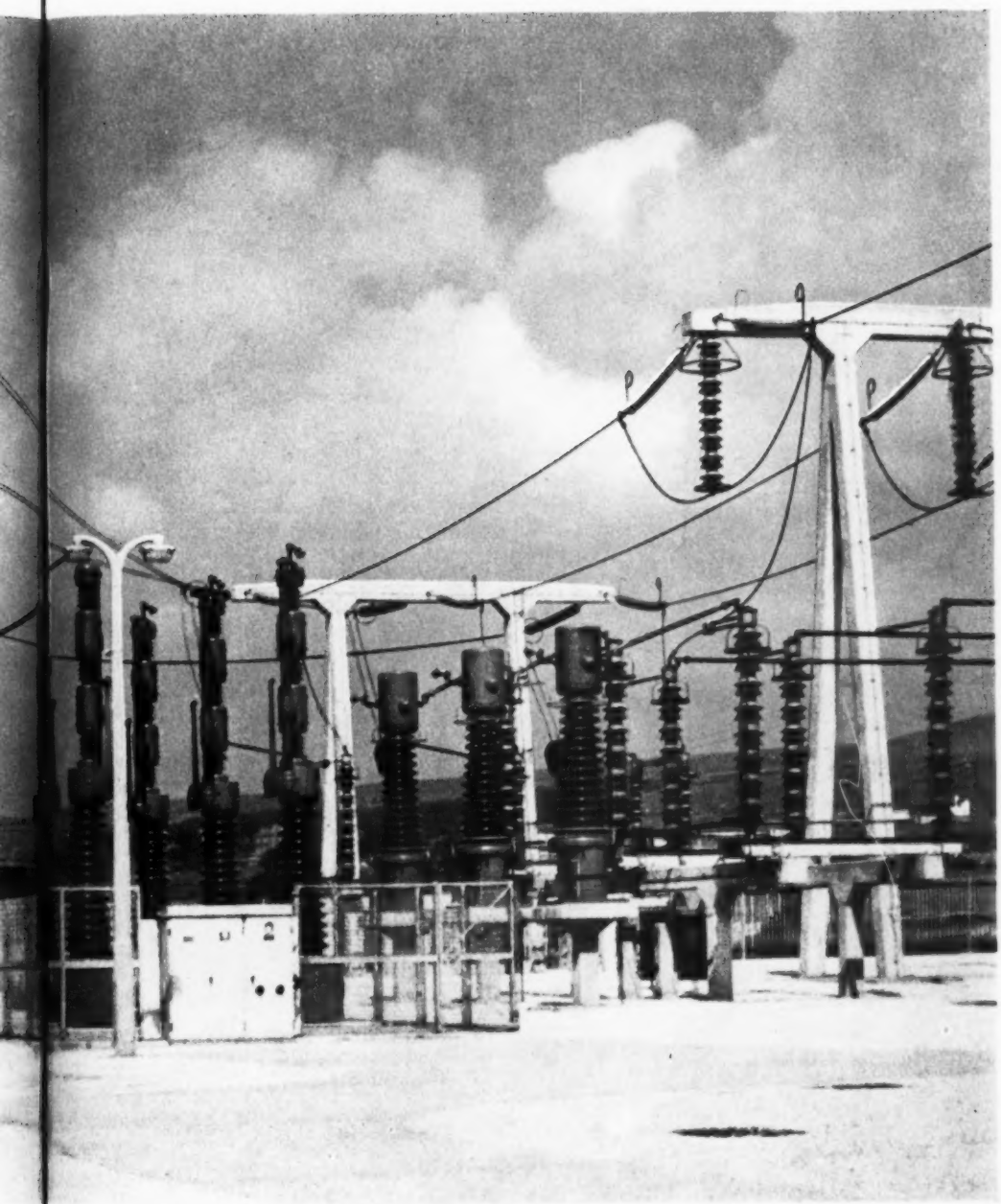
Fig. 1. (*left*) *Quarter-scale model of 'Oryx' turbo gas generator helicopter engine*

Fig. 2. (*above*) *Quarter-scale model of 'Deltic' marine diesel engine*



Part of the British Central Electricity Authority's 275 kV substation at Rochdale in the Nort
Company's 275 kV air-blast circuit-breakers having a breaking capacity of 7,500 MVA. Con
substations, at Connah's Quay, Harker and Smith

Correction. In the coloured illustration on pages 20 and 21 of the September issue of t
Tarraleah power station instead of to the similar Tungatinon



North Merseyside and North Wales Division. The substation is equipped with The English Electric MVA. Company also has contracts with the Central Electricity Authority for further new 275 kV and South a total of sixteen air-blast circuit-breakers.

ber 19 of this Journal, 'English Electric' circuit-breakers were inadvertently ascribed to ngatin on the other side of the river nearly opposite to Tarraleah.

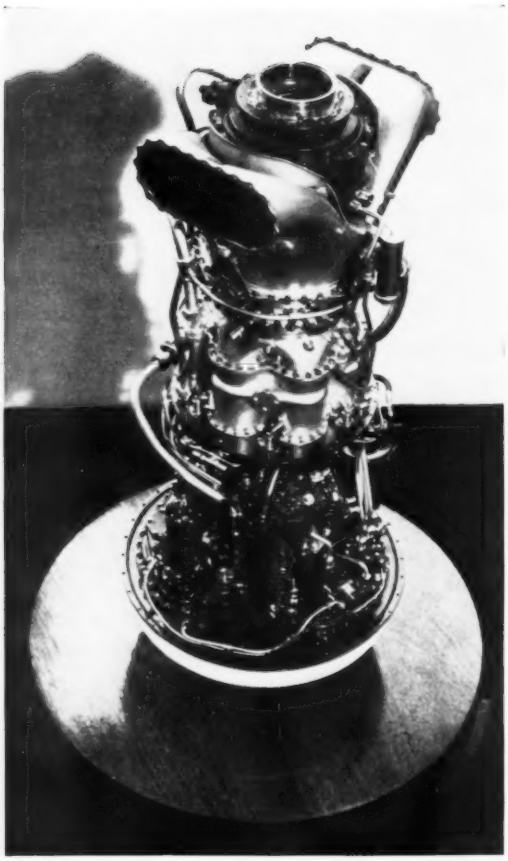


Fig. 3.—Quarter-scale model of 'Gazelle' free-turbine helicopter engine

but by showing two or three full-size engines and a range of perfect scale models, every product can be represented.

Models of all Napier engines, perfect miniatures of the actual prototypes, exact in every detail, are constructed at the Company's Flight Development Establishment, Luton, in a specially equipped workshop. The model shop was started in 1942, and has since grown into a self-contained department with its own machine shop and carpentry section, employing a total of seventeen highly skilled model-engineers.

Many outstanding models of Napier engines have been made by this team including those of the 24-cylinder 'Sabre' piston engine, the 'Eland' propeller-turbine, the 'Oryx' turbo gas generator helicopter engine (Fig. 1) and the 'Deltic' 18-cylinder marine diesel engine (Fig. 2). The most recent addition to this collection is the $\frac{1}{4}$-scale model of the new Napier free-turbine helicopter engine, the 'Gazelle' (Fig. 3). In many cases these models have had to be duplicated to meet the demands for their exhibition.

Static engine models are not the only type built in this workshop. Industrial models of power stations, rolling mills, ships' engine rooms, special

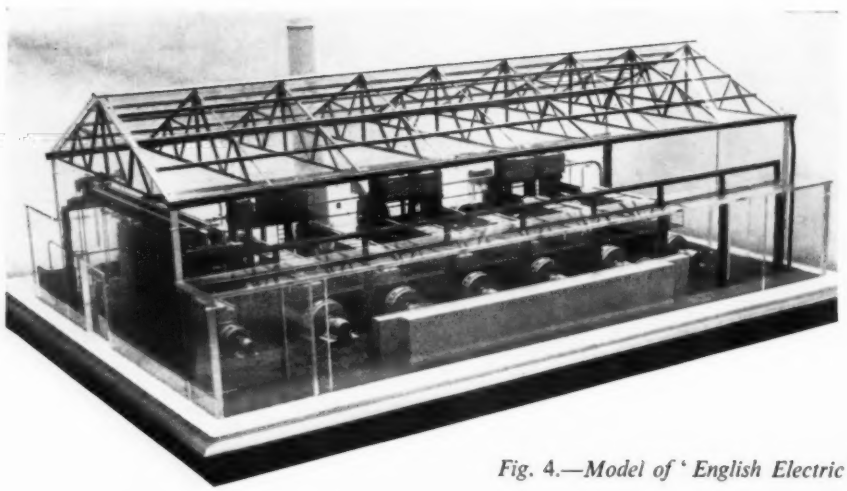


Fig. 4.—Model of 'English Electric' diesel power station.

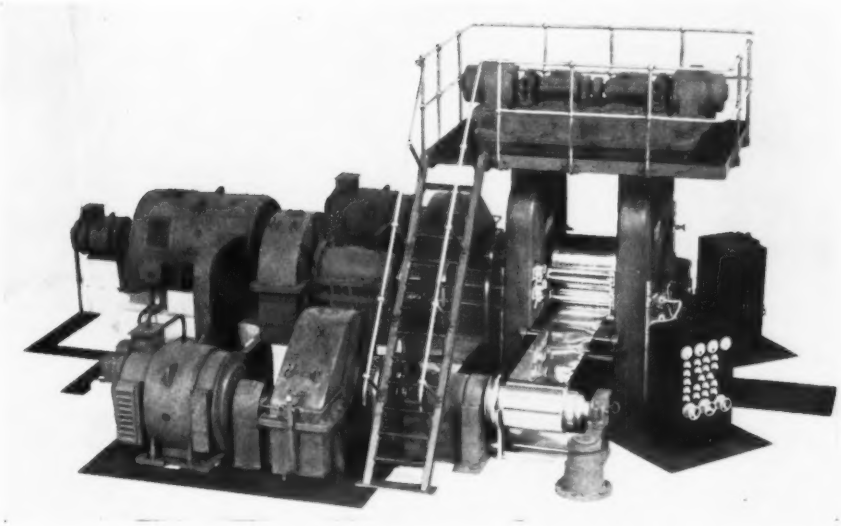


Fig. 5.—Model of 'English Electric' steel rolling mill

machines and armoured fighting vehicles have been constructed for other Companies within the 'English Electric' Group, examples of which are shown in Figs. 4, 5 and 6. One typical working model is that of a cross section through the 'Deltic' diesel engine (Fig. 7) showing a bank of three cylinders, the three crankshafts and six horizontally opposed pistons.

Model engineering of this calibre calls for a special temperament, for not only is the experience of a skilled precision engineer required, but also great patience and the extreme versatility necessary to tackle any job and work in any material. Perhaps the most important quality of all is a keen imagination, as apart from the external basic shape, most of these models are made without working drawings and many ingenious methods are necessary to reproduce difficult details in miniature.

When a model contains several identical parts, such as the 24 cylinder heads of the 'Sabre' engine,

Fig. 6.
Model of 'Comet' tank

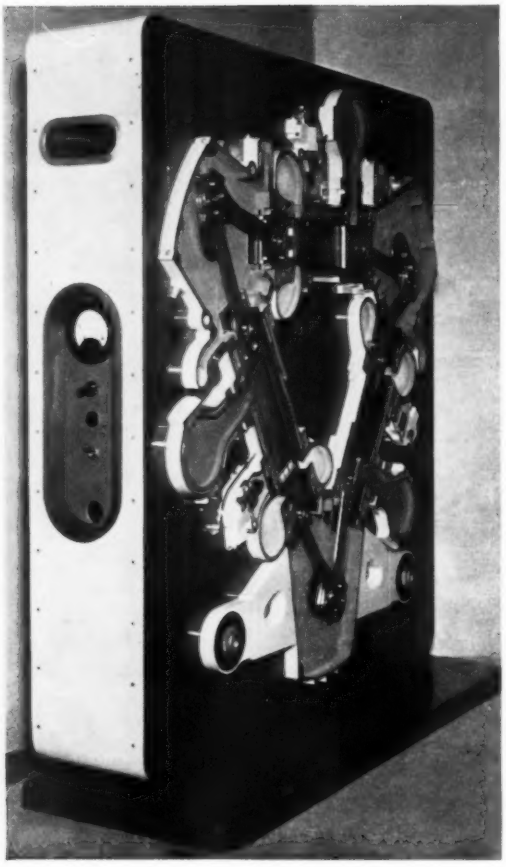


Fig. 7.—Half-scale working cross-sectional model of 'Deltic' marine engine

repetition is eliminated by the use of plastic mouldings. The dies for these, and the mouldings themselves, are all made in the model shop. In the construction of the quarter-scale 'Deltic' model (Fig. 2) over 9,000 nuts, bolts, washers and studs were used, of various sizes from 4 B.A. down to 14 B.A. (1/32 inch diameter). All models are made so that they can easily be taken to pieces, an important point when repairing those that have been damaged in shipment to and from overseas countries.

As the Napier Flight Development Establishment is essentially an aeronautical research organisation, the versatility and skill of the precision engineer is invaluable to the Company in many aspects apart from model making. Among the routine jobs allied to exhibition model making are the construction of space models and 'mock-ups' for testing new aircraft engine installations and guided missile configurations, and building wind tunnel models for research purposes.

The model engineer's appetite for precision and superlative finish has been more than satisfied at the Napier model shop, for in addition to models, the manufacture of prototype mechanisms for incorporation into the Company's aircraft engine installations, rocket engines and ram jets, is also part of the everyday work. Many of the intricate mechanisms used in these projects employ hydraulic valves and metering systems of unique design, in which sliding pistons made to limits of ·00005 inch and holes drilled five-thousandths of an inch in diameter are quite common practice. Work of this nature, together with the manufacture of scientific equipment and special tools for new processes, keeps the skill of these engineers at peak efficiency.

The manufacture of models to the high standard required to maintain the Napier Company's reputation for precision workmanship is of course expensive, but their cost is justified by their value at international exhibitions.

An Electric Motor Driven Gas Compressing Installation of the East Midlands Gas Board

By A. RAMSKILL of The English Electric Company, and R. HUTCHINSON, A.Fuel, M.Inst.Gas E., Divisional Engineer of the East Midlands Gas Board, Leicester and Northants Division.

This article describes an interesting application of electrical drives in the gas industry. The problem was to supply a simple, economical and reliable gas-main compressor drive having considerable freedom in speed adjustment. Since the compressor power varies widely with the speed, two-speed slipring motors, rated at 70 h.p. for the maximum speed duty, were found to be the most economical solution.

IN THE AREA OF THE East Midlands Gas Board there is a gas grid system which *inter alia* serves the principal towns in the counties of Leicestershire, Rutland and Northamptonshire. The gas is pumped southwards from Derby where it is received from the Avenue coke oven plant near Chesterfield and the Stanton Ironworks coke ovens near Nottingham. The towns served in this southern zone all receive their gas from the 'backbone' main, either by direct connections or via comparatively small-sized branches which spread from it rather like the ribs from the human spine. The rib or branch which serves Melton Mowbray, Oakham and Uppingham is particularly long, and the pressure of gas in the 'backbone' main itself is insufficient to overcome the pressure drop on this 30 mile lateral. To augment the pressure, therefore, a recompression plant has been installed at Sileby which is an interesting example of unusual electric motor application for gas compression duties.

At current capital costs it is cheaper to lay comparatively small mains over long distances and employ high gas pressure than to lay large mains and avoid recompression, as the cost of pumping is less than the interest and depreciation charges associated with large pipes.

In this installation it is possible to arrange a good load factor on the compressors by using the gasholder storage capacity in the three towns served, as the compressors do not have to handle directly the load imposed by the consumers. The gasholders, in effect, 'peak shave' the load. There are, however, the difficulties associated with the seasonal changes and the week-end and holiday periods which call for special consideration, as will be evident in the description which follows. It will be understood that the horse-power absorbed in a pipe system has a square-law characteristic, and the plant installed has been selected with a view to keeping to a minimum the total costs involved, not only those associated with the pumping of the gas but also including the interest and capital depreciation charges of the plant.

The installation comprises duplicate sets of Donkin piston-type compressors (Fig. 1), one to act as standby to the other, each driven through vee ropes by an 'English Electric' 70/35 h.p. 1,460/730 r.p.m. change-pole medium voltage motor of the slipring screen-protected type (Fig. 2). The motors are mounted outside the dangerous zone associated with the compressors, the drive being taken through gas-tight glands incorporated in wall boxes. The motors are controlled by Brookhirst Switchgear starting panels which incorporate twelve continuously rated rotor resistances to enable a speed reduction of 20% to be obtained on each of the two speeds.

The 415 volts 3-phase 50 cycles supply to the starters is controlled by 'English Electric' Combination fuse-switchgear.

It is with a view to obtaining the best possible

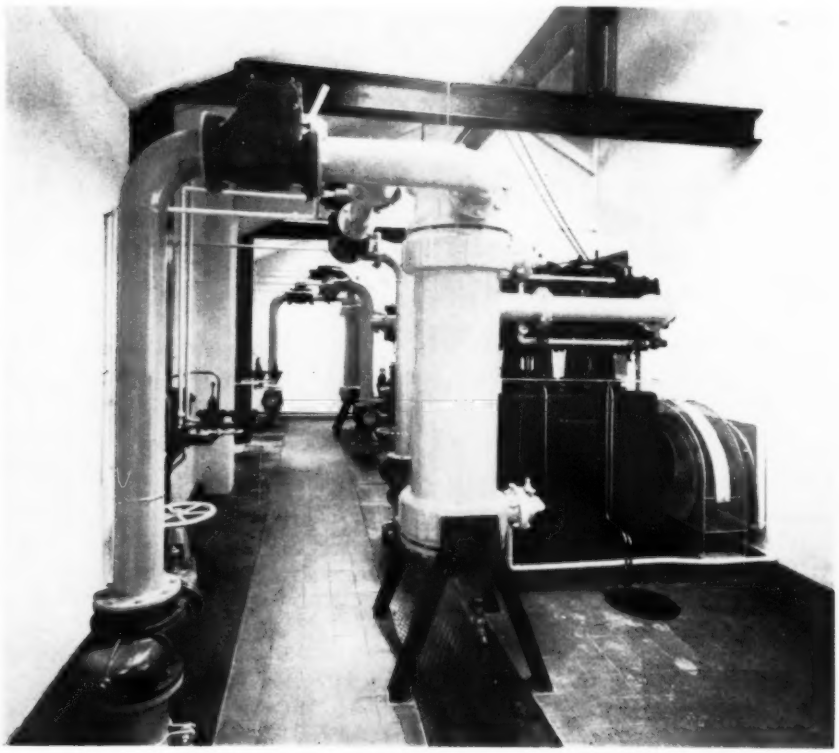


Fig. 1. The piston-type gas compressors

load factor that change-pole motors and rotor resistance speed control have been adopted, the two speeds of the motor catering for the winter and summer-time gas loads (the winter load is approximately twice the summer load) and the speed reduction feature doing much to meet the inter-seasonal, week-end and holiday demands. The horse-power involved is not large, and although the electrical losses associated with rotor resistance are comparatively high as a percentage of the total power (equivalent to the percentage speed reduction obtained), bearing in mind the square-law power ratio, the scheme is economic.

The setting of the rotor resistances is not automatic, but is made as necessary when the volume to be handled by the compressors and the approximate running speed have been calculated. (The information is transmittible to the local Sales and Service Superintendent by the telephone). Apart from the visit for this purpose each morning, when recorder charts are changed and lubricators filled, the plant runs completely unattended.

The motor control panels are equipped with repeater time-switch starting gear and high gas pressure stop switches. The former are used to start the plant between 5 a.m. and 9 a.m., giving eight half-hourly start impulses, and the latter to shut down the plant when the gasholders in the three towns are full, by the operation of automatic gasholder valves. The following illustration of a typical day's working will enable the significance of these features to be appreciated.

On a Sunday morning in, say, the month of March, the time-switch starts the compressing plant at 5 a.m. The compressor runs up to speed and compresses the gas in the main, but due to the gasholders still being full (being Sunday the consumers have not yet risen) the pressure rises and the high-pressure limit switch shuts down the plant again. At 5.30 a.m., and again at 6 a.m.,

this procedure is repeated. At 6.30 a.m., however, the local demand having lowered the gas-holders, the automatic holder valves have opened, so that continuous running follows after starting. Subsequent repeater starting impulses at 7 a.m., 7.30 a.m., 8 a.m., 8.30 a.m. and 9 a.m. do not, of course, have any effect. The compressing plant continues to run, say, at 15% less than full speed, the figure calculated by the Grid Control Office, but due to it being a much warmer evening than anticipated the holders are full again by 12 midnight. At this time the holder valves shut, the gas main pressure rises and the plant shuts down until it is re-started the next morning at 5 a.m.

It will be appreciated that it is difficult to anticipate the gas load and therefore the compressor speeds, and despite the best estimates that can be made there is inevitably the possibility of running the plant for a long period wastefully at very low load.

In addition to these interesting control gear features, this plant incorporates an uncommon compressor starting and stopping equipment, whereby time delays incorporated in the motor starters operate a special gas pressure relief valve which interconnects the compressor outlet and inlet mains. The opening of this valve enables the machine to run up to speed without the load of the gas pressure in the cylinders, and by means of an inverse time delay the relief valve is held open as the plant is shut down, to avoid the risk of a strained crankshaft. This relief valve also gives protection when the plant is running, against excessive outlet pressure, and on a shortage of inlet pressure it prevents a vacuum in the inlet main should there be any interruption in the incoming supply.

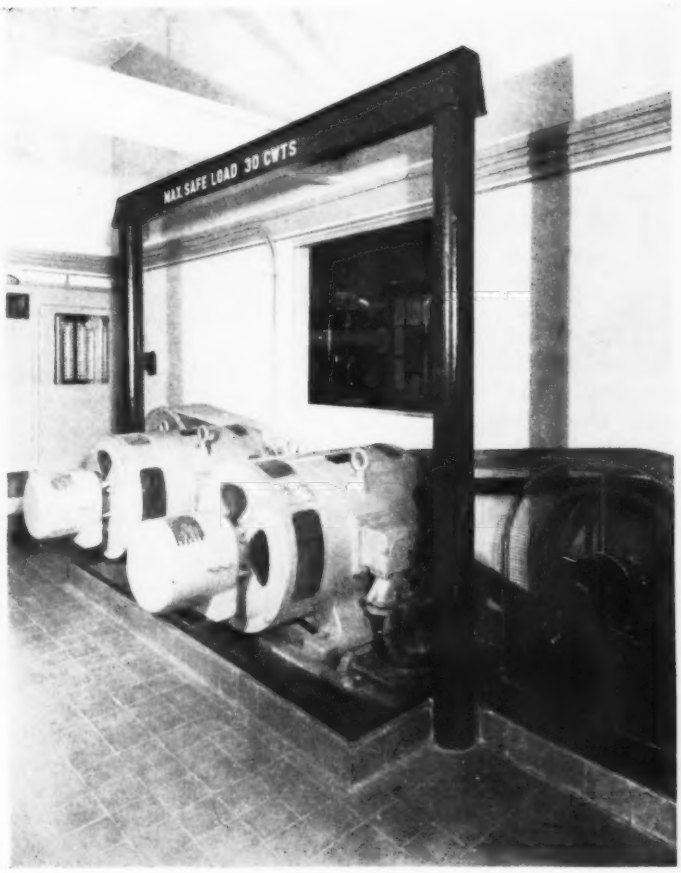


Fig. 2.—The 70/35 h.p. 2-speed motors driving the compressors through vee ropes

The compressors are water jacketed, and the cooling system incorporates a thermostat switch which operates in the stop circuit of the main motors as a safeguard against failure of the water circulating system.

The cooling water is circulated by electric motor driven centrifugal pumps, the water passing through the gas compressor cylinder jackets and the gas after cooler, and the heat being dissipated normally by circulation through a large water tank adjacent to the plant. Should the temperature in this tank exceed a pre-set limit, a magnetically operated town-water valve is opened by means of a water thermostat, whereby cold water displaces the warm water in the tank until the temperature level has been reduced to a safe limit.

Diesel-Electric Locomotives in Jamaica

THE ISLAND OF JAMAICA, which is one of the largest of the Caribbean islands, is approximately 140 miles long and 50 miles wide. Parts of the country are flat alluvial plain, but most of it is extremely mountainous and transport is difficult by reason of the steep gradients and sharp curves. The island's economy has been essentially agricultural in the past, the principal crops being sugar, citrus fruits and bananas, but to-day the development of the vast bauxite and other mineral deposits is becoming a significant factor.

The standard gauge Jamaica Government Railway (Fig. 1) runs from Kingston, the largest town and the main port, to Montego Bay, with a branch from Spanish Town to Port Antonio. From Kingston to Clarendon the line is practically straight and flat with a maximum gradient of 1 in 100, but from Clarendon to Montego Bay and from Spanish Town to Port Antonio the profile rises to 1,700 ft and is characterised by gradients of 1 in 30 combined with almost continuous reverse curves of 330 ft radius, a combination which is exceptionally severe for a standard gauge line. The profile of the line from Kingston to Montego Bay shown in Fig. 2 will give some indication of the problems which arise in operating freight and passenger services over the railway.

Until recently, the bulk of the traffic was handled by oil burning steam locomotives, although small diesel railcars have been used for many years on local passenger services and a daily express train between Kingston and Montego Bay has been operated by two-coach diesel units. Following a decision to modernise the railway, a study was made of different forms of motive power and it was decided to abandon steam and to change over to diesel locomotives. An enquiry was issued calling for locomotives capable of hauling trains of 150 tons over the hill sections and 300 tons on the other sections. The diesel locomotives had of course to be designed to meet the difficult physical conditions, which implied satisfactory riding on straight track and on the extremely sharp curves, adequate protection against dust as well as against torrential rain and tropical humidity, robust construction, simplicity of operation and low maintenance.

Overseas railways often have unusual conditions

Fig. 1.—The standard gauge Jamaica Government Railway

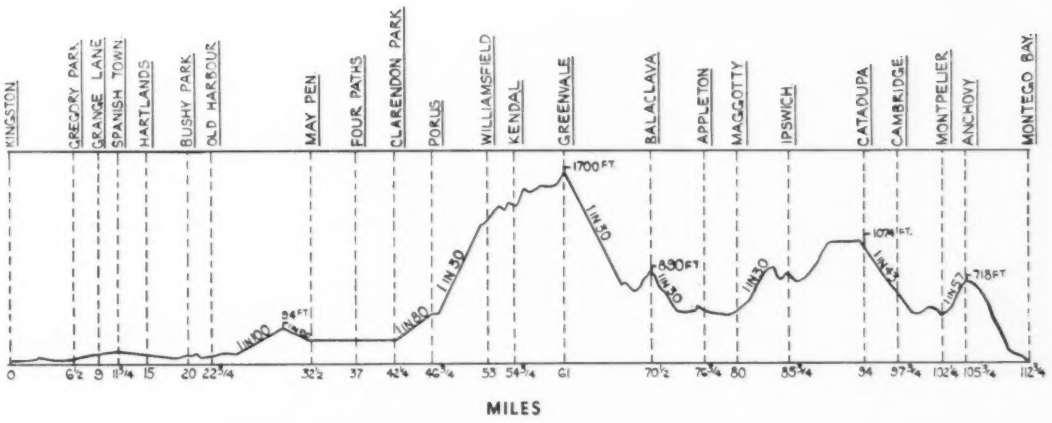


Fig. 2.—Profile of line from Kingston to Montego Bay

to contend with which can be pitfalls for the designer—for example, trouble was experienced with certain diesel railcars in Jamaica due to the presence of dried banana trash on the lines which was drawn into the radiator air intakes and blocked the radiator elements. Emphasis was therefore laid on the need to meet local conditions of operation.

An order for seven 750 h.p. diesel-electric locomotives was placed through the Crown Agents with The English Electric Company, and following the very successful results in service, the order was

Fig. 3.—One of the ten 'English Electric' 750 h.p. diesel-electric locomotives

subsequently increased to ten, all of which have now been completed and one is shown in Fig. 3. The general arrangement of these locomotives is shown in Fig. 4. The superstructure is carried on two two-axle bogies, each axle being driven by a nose-suspended motor.

Main Dimensions and Ratings

Gauge	4′ 8½″
Length over buffer beams	41′ 11½″
Height above rail level	13′ 5½″
Maximum width	9′ 6″
Distance between bogie centres	22′ 6″
Bogie wheelbase	8′ 6″
Minimum radius of curve negotiable	240′ 0″
Weight in working order	63·5 tons
Maximum axle load	16 tons
Maximum tractive effort (25% adhesion))	35,500 lb
Continuous rated tractive effort	24,900 lb
Maximum safe speed	60 m.p.h.
Engine rating, at 850 r.p.m.	750 b.h.p.

Power Equipment

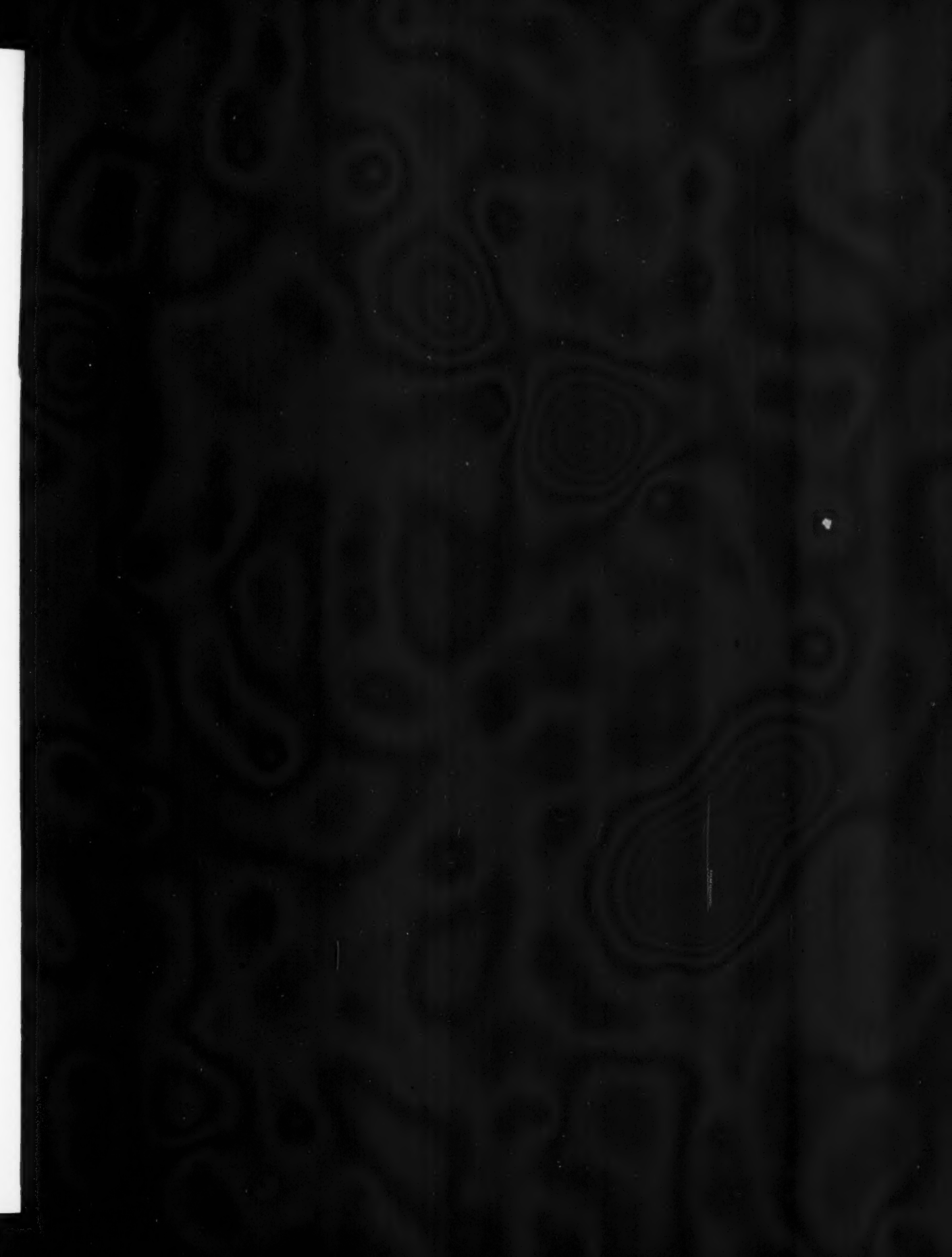
Each locomotive is powered by an 'English Electric' 6SRKT diesel engine having a continuous traction rating of 750 b.h.p. at 850 r.p.m. The engine is a six cylinder in-line four-stroke unit, pressure charged by an exhaust gas turbo-charger, and is solidly coupled to a flange-mounted single bearing generator. The complete power unit is mounted on resilient supports which relieve the engine from stresses set up by any flexure of the underframe. Power from the main generator is transmitted to the road wheels through four six-pole axle-hung traction motors, driving the axles through single reduction spur gearing. The motors are permanently connected in series-parallel, with three stages of field weakening to make full engine output available up to 50 m.p.h.

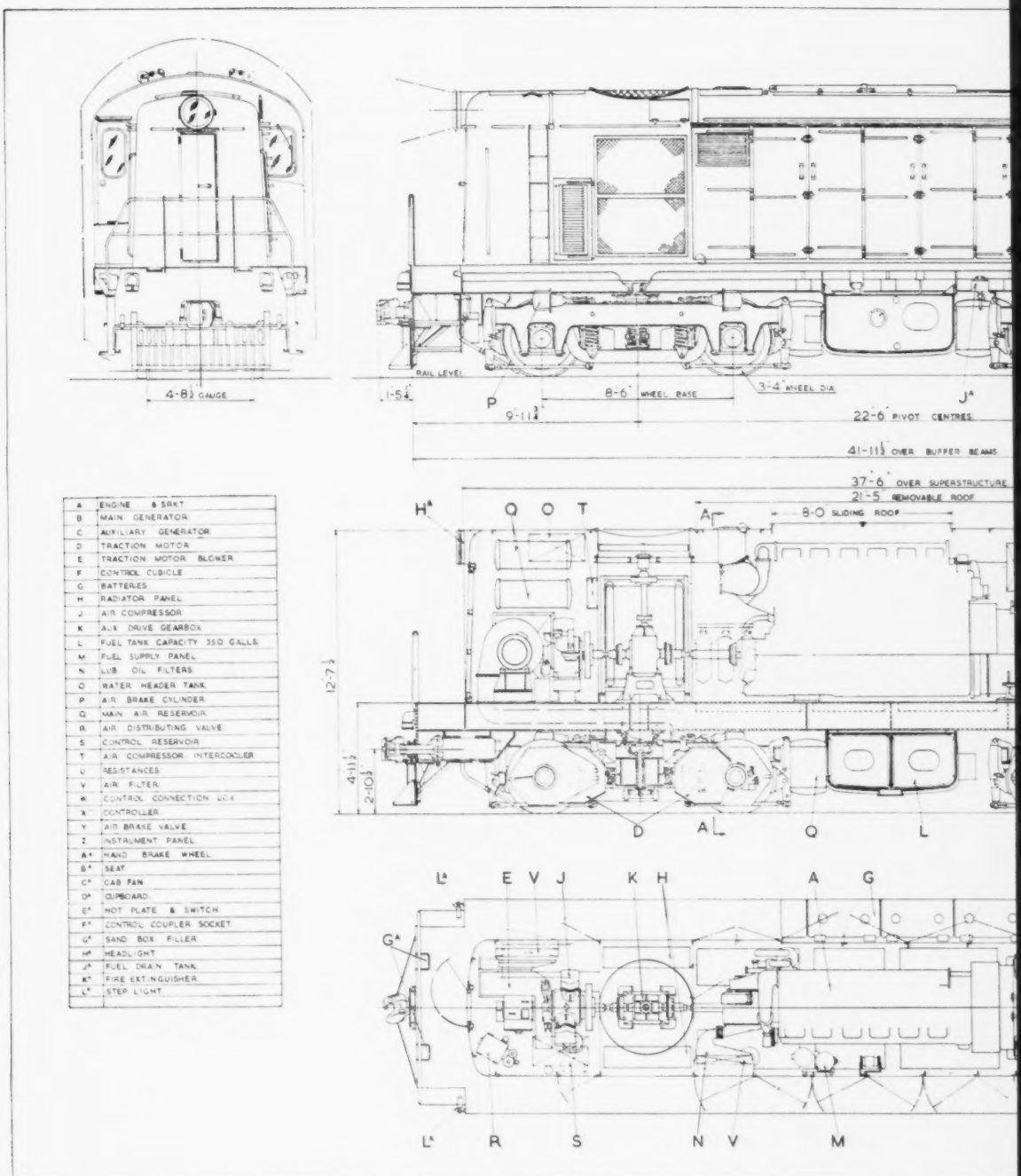
Control of the locomotives is very simple. The driver has, apart from the brake controller, a compact power controller with two handles. One handle is used for setting the reversers for the required direction of travel, and the other controls the power developed by the engine. The method of control is of special interest because of its simplicity and the excellent performance characteristics which it provides. The main control handle operates a small number of contacts which establish the basic electrical circuits, but variation in power is effected pneumatically. Movement of the control handle causes the air pressure in a control pipe to assume a value corresponding to the position of the handle. This air pressure actuates a spring-loaded piston on the engine governor, so adjusting the engine speed. Electrical contacts on the governor actuate a motor-operated torque regulator which varies the generator field to maintain the load imposed on the engine at the correct figure corresponding to the engine speed. The full power corresponding to any position of the master controller handle is available over the range of locomotive speed, the torque regulator initiating field weakening of the traction motors as required. With this system, the engine speed is continuously variable from idling to full rated speed ; the driver sets the power output to suit traffic requirements and the loading is automatically adjusted to this value irrespective of locomotive speed ; the engine never runs at a higher speed than the minimum needed to produce the power demanded ; fuel consumption and maintenance are substantially less than with a stepped speed system, and the equipment and train lines required are less than with other systems.

The radiator fan and Westinghouse compressor are driven mechanically from the engine crankshaft. The fan is mounted in the roof and driven through a gear-box, a centrifugal clutch limiting stresses in the fan blades and driving shafts due to sudden acceleration or deceleration of the engine. Lead-acid batteries, of the D.P. Battery Company's special diesel traction type, are used for engine starting. An overhung auxiliary generator provides power at 110 volts for battery charging, lighting, control equipment and auxiliaries.

Mechanical Structure

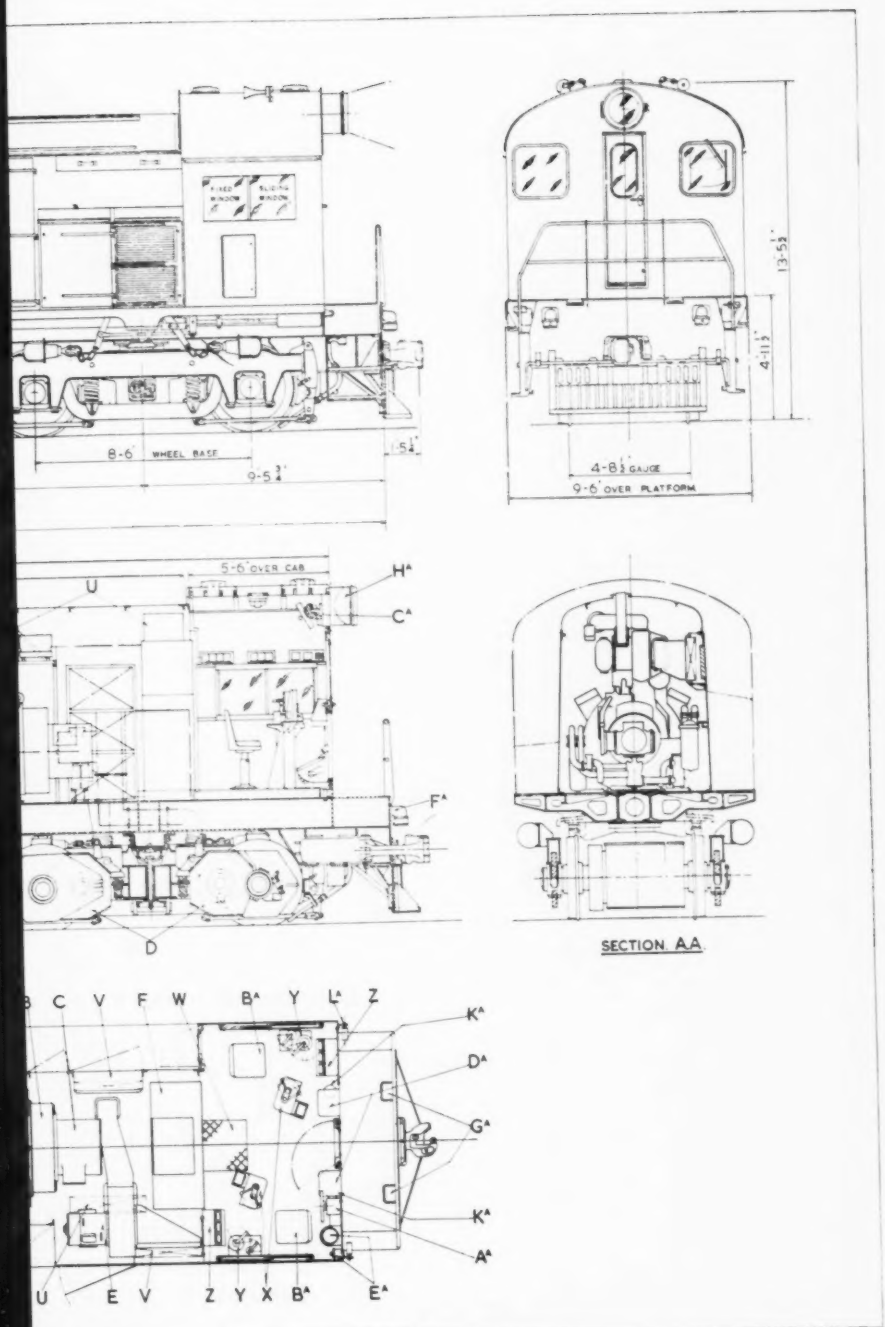
The superstructure is of the narrow bonnet type, with a full-width driving cab at one end, so providing good visibility in either direction of travel. The bonnet is divided into three compartments. The first houses the air compressor, air brake equipment and one traction motor blower ; in the second are the two side radiator panels, with the





A	ENGINE 6 SRKT
B	MAIN GENERATOR
C	AUXILIARY GENERATOR
D	TRACTION MOTOR
E	TRACTION MOTOR BLOWER
F	CONTROL CUBICLE
G	BATTERIES
H	RADIATOR PANEL
J	AIR COMPRESSOR
K	AUX DRIVE GEARBOX
L	FUEL TANK CAPACITY 350 GALLS
M	FUEL SUPPLY PANEL
N	LUB OIL FILTERS
O	WATER HEADER TANK
P	AIR BRAKE CYLINDER
Q	MAIN AIR RESERVOIR
R	AIR DISTRIBUTING VALVE
S	CONTROL RESERVOIR
T	AIR COMPRESSOR INTERCOOLER
U	RESISTANCES
V	AIR FILTER
W	CONTROL CONNECTION BOX
X	CONTROLLER
Y	AIR BRAKE VALVE
Z	INSTRUMENT PANEL
A*	HAND BRAKE WHEEL
B*	SEAT
C*	CAB FAN
D*	CUPBOARD
E*	HOT PLATE & SWITCH
F*	CONTROL COUPLER SOCKET
G*	SAND BOX FILLER
H*	HEADLIGHT
J*	FUEL DRAIN TANK
K*	FIRE EXTINGUISHER
L*	STEP LIGHT

Fig. 4.—General arrangement of the


FIXED WINDOW
SLIDING WINDOW
8-6" WHEEL BASE
9-5¾"
1-5½"
13-5½"
4-11½"
4-8½" GAUGE
9-6" OVER PLATFORM
5-6" OVER CAB
U
H^A
C^A
F^A
D
SECTION AA
B C V F W B^A Y L^A Z
K^A
D^A
G^A
K^A
A^A
U E V Z Y X B^A E^A

roof mounted radiator fan ; and the third contains the power unit and a second traction motor blower. The control equipment is mounted in a dust-proof cubicle which forms the front wall of the driving cab. Each end of the body has a wide shunter's platform with steps at each side and a protective handrail, to enable shunters to cross from side to side and to carry station pilots. The driving cab has two driving positions in diagonally opposite corners. Entry into the cab is by a door opening on to the rear platform, and a second door in the front of the cab gives access to the foot-walk along the side of the bonnet.

The superstructure framing is fabricated from steel sections, and large aluminium-alloy doors provide access for maintenance. The underframe is fabricated from two main 'I' section longitudinals and two channel section sole bars, reinforced and cross braced, with drag boxes at each end to accommodate the centre couplers. The underframe flooring is welded oil-tight to protect the running gear and traction motors from fuel and lubricating oil, a feature which eliminates fire hazard due to the ignition by brake shoe sparks of oil soaked accumulations of dust.

The bogie frames are of riveted and welded construction, the side members being box-section fabrications riveted to a fabricated transom and headstocks. The superstructure load is carried on a large diameter centre bearing which also transmits the thrust from the bogie. Phosphor bronze liners are fitted on the bearing surfaces, which are provided with oil-bath lubrication and protected from dust by a felt ring. Manganese steel liners are fitted on the thrust faces. The bolster is a steel casting, resting on laminated elliptic springs carried on a spring plank which is connected to the bogie frame by inclined swing links. The bogie frame is supported on four groups of coil springs which in turn are carried on forged steel equalising beams. The roller-bearing axleboxes, axlebox guides and bolster thrust rubbing faces have renewable manganese steel liners.

The locomotive is fitted with air operated brakes, with individual brake cylinders operating clasp brakes on each wheel. A handbrake operates on the bogie adjacent to the driving cab. Air operated sanding is provided at each end of the locomotive.

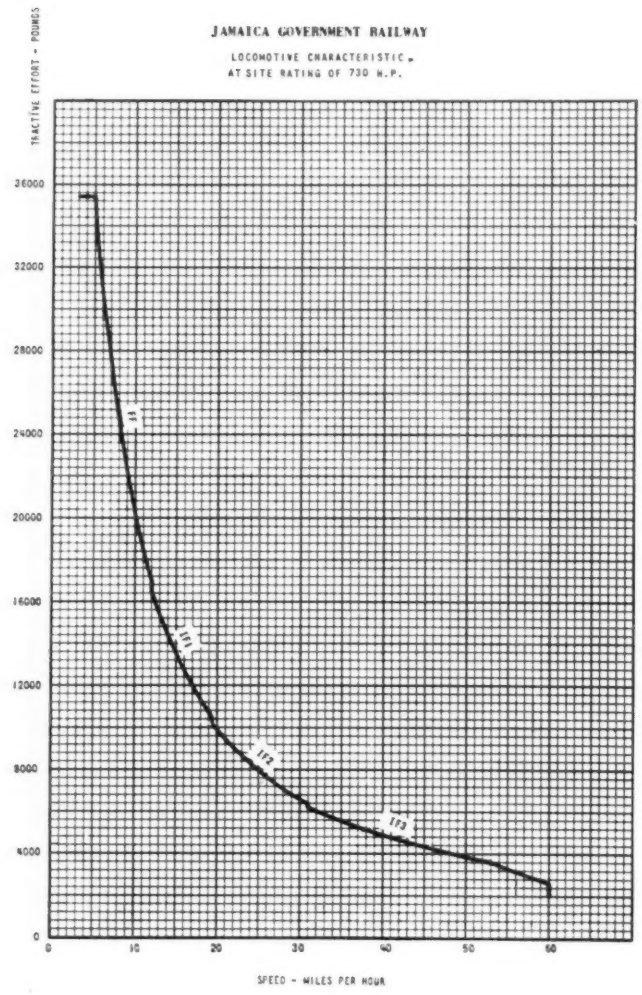
Protection against Climatic Conditions

All air for the engine and for the ventilation of the equipment is filtered. The engine air is drawn through oil wetted metal filters in the locomotive sides and ducted directly to the pressure charger intake. Air for the traction motors is drawn through similar filters by the traction motor blowers and ducted to the traction motors, flexible bellows being used for connection between the ducts and the motor inlets. Engine room air enters through large-area filters at the generator end, and is extracted at the front end by the radiator fan, the area of the opening in the radiator compartment partition being such as to provide an air flow through the engine room of several thousand cubic feet per minute. The air passing through the radiator elements does not enter any part of the locomotive other than the radiator compartment. Air filter elements are protected by louvres of special shape to prevent ingress of tropical rain.

Performance

The locomotives are universal units suitable for both passenger and freight trains and having sufficient power to improve on existing steam locomotive performance whilst still being economical in shunting service. This enables the fullest use to be made of the high availability inherent in a well-designed diesel-electric locomotive, and permits one standard type of unit to fulfil all traffic requirements with attendant advantages in rostering and maintenance. The speed/tractive-effort characteristic for site conditions, i.e., with the engine set to deliver 730 h.p., is shown in Fig. 5.

Although a maximum trailing load of 150 tons per locomotive was specified for operation over the hill sections, tests at site have enabled a load limit of over 200 tons per locomotive to be established for these sections. This compares favourably with the normal limit of 150 tons for existing 110 ton eight-coupled steam locomotives. Multiple unit operation enables double headed trains of up to 430 tons to be hauled up the long 1 in 30 gradient between Porus and Williamsfield when working the alumina traffic, a performance which has relieved a bottleneck that threatened to dislocate traffic as the output of alumina increased. Multiple unit operation is also of value in that by using a single



FF Full field on traction motors
IF1, IF2, IF3 Three stages of field weakening on traction motors

Fig. 5.
Speed/tractive-effort characteristic of locomotives for site conditions

unit on the plains section and a double unit over the hills, it is no longer necessary to break and re-marshal freight trains at the foot of the hills, with consequent saving in time and increase in line capacity.

The full realisation of the performance capabilities of diesel locomotives is of course dependent upon the adoption of a regular maintenance procedure and the provision of adequate maintenance facilities. The Jamaica Government Railway arranged for experienced engineers from the manufacturer to visit Jamaica, and after a detailed examination of existing installations, plans were prepared for the conversion of the workshops and running sheds for the new type of motive power. The first-hand knowledge available as a result of these visits enabled a comprehensive yet economical scheme to be carried out, making the fullest use of available resources and equipment. For the same reasons, selected members of the Railway staff were sent to England for periods of training at The English Electric Company's works, thus ensuring that a nucleus of trained fitters was available when the locomotives arrived. This action, together with the provision by the Company of a resident engineer to commission the locomotives and instruct the staff, has resulted in the change-over from steam to diesel traction proceeding smoothly and well.

RECENT 'ENGLISH ELECTRIC' AND 'NAPIER' TECHNICAL PAPERS

'English Electric' Papers

CALVERLEY, H. B., B.Sc.(Eng.), A.M.I.E.E., JARVIS, E. A. K., B.Sc.(Eng.), A.M.I.E.E., and WILLIAMS, E., B.Sc.(Eng.), A.M.I.E.E., Traction Department. *Electrical equipment for rectifier locomotives.* Institution of Electrical Engineers, London, 14th March, 1957.

The single-phase 50 c/s system of railway electrification has developed extremely rapidly and has been adopted in recent years by France, Turkey, Portugal, the Belgian Congo and Great Britain. Of the many types of locomotive possible, the rectifier type is becoming more and more widely favoured, owing to its combining the best possible traction motor with the lightest form of convertor.

The paper discusses various types of power circuit which have been or could be used on rectifier locomotives, including h.v. and l.v. control systems, types of on-load tap-changing circuit, buck-boost control systems, stepless control systems, bridge and bi-phase rectifier circuits, and methods of connecting motors. Different types of tap-changer, transformer, and rectifier are discussed. The operation of the motor on current with ripples is compared with d.c. operation, and the many factors which influence the choice of the ripple current are analysed.

The principal aim of the paper is to bring together the characteristics of transformers, tap-changers, rectifiers and motors, and to discuss the advantages and disadvantages of the various ways in which these items can be put together to form a complete equipment.

No ideal solution is found, as the authors consider that the development potential is too great for any existing equipment to be regarded as final.

CALVERLEY, T. E., B.Sc.(Eng.), Ph.D., A.M.I.E.E., Chief Engineer, Rectifier Department, and TAYLOR, D. G., B.Sc.(Eng.), Nelson Research Laboratories. *Circuit calculations for rectifier locomotives and motor coaches.* Institution of Electrical Engineers, London, 14th March,1957.

The increasing use of rectifier locomotives and motor coaches has focused attention on the limitations of accepted rectifier theory in the calculation of performance of bi-phase and single-phase bridge-connected rectifier circuits. Most industrial rectifier installations exceeding a few kilowatts in rating are supplied from a 3-phase system, and are designed to operate with 6 or 12-phase output on the d.c. side, while sometimes in very large installations it is necessary to operate with up to 72-phase output. In these conventional multi-phase equipments the ripple current, which is associated with undulations in the output voltage, is superimposed on the output direct current, but is sufficiently small to permit for the purpose of calculation the assumption of a d.c. circuit of infinite inductance. This assumption leads to considerable simplification of the theory. Unfortunately it is not tenable in the circuits discussed in the paper, as it is found that the presence of the ripple current in the d.c. circuit has a profound effect on the operation of the whole equipment.

The paper outlines the calculations for bi-phase and bridge circuits, based on the accepted 'infinite inductance' theory, and derives the direct voltage at the motor, ripple current in motor circuit, power factor in the a.c. supply, harmonic currents in the a.c. supply, and other related quantities. The inaccuracies in the results of these calculations are pointed out.

A description follows of a new approach to rectifier problems by means of which solutions to both transient and steady-state problems can be obtained, taking proper account of resistances, inductances and capacities in all parts of the circuit. The problems are treated as circuit problems, the equilibrium equations being established in terms of mesh currents and expressed as simultaneous first-order differential equations. These are solved by means of a digital electronic computer, DEUCE, whose logical facilities are used to take account of the valve action of the rectifying elements.

Results of calculations are supported by tests which were carried out in conjunction with British Railways on the Lancaster-Morecambe-Heysham section. A description of this electrification has appeared elsewhere.* The operation of rectifier locomotives is discussed in the light of further calculations based on variations of a typical design.

VAN DORP, S. D., B.Sc.(Eng.), A.M.I.Loco.E., and GRAHAM, G. W., B.Sc.(Eng.), Grad.I.Loco.E., Traction Projects Engineering Department. *Modern methods of train performance calculation.* Institution of Locomotive Engineers, Leeds, 25th April, 1957.

The paper discusses the various aspects of train performance amenable to calculation, and their value to both railway operators and locomotive constructors. It refers briefly to various methods which have been devised to facilitate such calculations and describes in detail three widely differing modern computers. One, constructed by Manchester University, is an electrical analogue type ; another, built by Messrs. Amsler and designed in collaboration with The English Electric Company, is a mechanical analogue computer ; the third is the DEUCE digital computer as programmed for this particular purpose.

PARISH, A. R., B.Sc.(Eng.), A.M.I.E.E., Mem. A.I.E.E., Switchgear Engineering Department. *Aluminium and aluminium alloy busbars.* Aluminium Development Association, Symposium on Aluminium in Electrical Engineering, London, 16th-17th May, 1957.

Aluminium has been used, to a limited extent, for busbars for more than 30 years, but, despite economic attractions, the wide adoption of this material has been delayed by the difficulties of making joints and the relatively poor mechanical properties. Recently, aluminium manufacturers have offered special alloys intended for use as electrical conductors ; these have a strength of some three times, and a conductivity 92%, that of electrical purity aluminium. This improvement in mechanical properties has made the use of aluminium for conductors subjected to heavy short-circuit forces a much more practicable proposition, particularly as the alloy concerned is suitable for extrusion into high-strength angle and channel sections.

Before aluminium conductor can be applied with confidence, a simple jointing technique which gives consistent results is essential. The tinning process normally used with copper is impracticable because of the adherent oxide coating on the aluminium, and the conventional method is by scratch brushing under grease. The success of this latter method depends on the integrity of the operator, and a simpler technique would be preferable. Recently, a proprietary jointing compound has been introduced which it is claimed will produce satisfactory joints if merely spread on copper or aluminium before bolting or clamping. Various of the jointing techniques were tested under load-cycling conditions over some months, by exposure to corrosive atmosphere and under short-circuit tests. The conclusions from the tests were that the ' scratch brushing under grease ' procedure was satisfactory but that the use of the proprietary jointing compound showed the greatest promise.

A number of installations have been examined by the author in which aluminium has given satisfactory service for many years, and this experience together with the encouraging results of the tests have led to the conclusion that aluminium could be used much more widely.

GOMPERTS, R. J., M.A.(Cantab), Lic. ès Sci., Assistant Chief Research Engineer, Guided Weapons Division. *Computing applications where analogue methods appear to be superior to digital.* British Institution of Radio Engineers, Convention on Electronics in Automation, Cambridge, 29th June, 1957.

In solving scientific engineering problems and in design studies the first step consists of formulating the mathematical analogue of the problem which is to be studied. It is then a matter of convenience which means are employed to realise this mathematical model—analogue or digital. There are therefore no *a priori* reasons why either method is to be preferred and the choice will be dictated by the exigencies of the problem and the equipment in existence.

* *The English Electric Journal, March* 1954, *Vol.* 13, *No.* 5, *p.* 185.

Some advantages of analogue machines are quoted and three particular problems are studied for which analogue methods appear to be superior, namely the computation of non-linear heat flow, noise analysis, and the Monte Carlo method for solving neutron collision problems.

COWLIN, F. J., (the late), O.B.E., M.I.Mech.E., A.M.I.Mar.E., Chief Engineer, Steam Turbine Division 1943-1956, and VEITCH, A. F., A.I.Mar.E., Chief Designs Engineer, Steam Turbine Division (Marine). *Recent developments in British naval main propulsion steam turbines.* The Institute of Marine Engineers, 8th October, 1957.

The purpose of this paper is to show the considerable advances that have been made in British naval main propulsion steam turbines since the end of the 1939-45 war. These advances include improvements in design and manufacture which have enabled higher steam conditions to be utilised, the overall result being improved performance which, together with weight and space reduction, results in increased endurance.

The initial impetus resulted from war-time experience and led very quickly to the three designs of Daring turbines, one of which is discussed in detail.

The next step was an investigation into all the factors affecting performance, endurance, etc., and so far as the main propulsion turbines are concerned, the various problems and resulting improvements are discussed in that section of the paper dealing with Y.E.47A.

The Y.E.A.D. 1 turbine design which is described in detail is a further development of the Daring III design and is a logical step forward following the Y.E.47A investigations.

The special requirements of the anti-submarine frigates necessitated turbines which incorporate some rather unusual design features, and these are described under the heading of Y.100, together with the reasons and shore and sea trials results.

'Napier' Papers

DE GUERIN, D., and HALL, L. F., Research Department, D. Napier & Son Ltd. *An experimental comparison between three types of heavy duty thrust bearing.* Institution of Mechanical Engineers, Conference on Lubrication and Wear, 1st-3rd October, 1957.

The paper describes tests of the three principal types of plain thrust bearing, namely the hydraulic bearing, the fixed pad bearing, and the tilting pad or Michell bearing.

The bearings were designed to carry loads of the order of 100 tons at speeds up to 3,000 r.p.m. and were approximately 2 feet in diameter. Special test equipment was built to determine limiting loads, power losses and local temperatures, and this is briefly described. Additional tests were carried out on smaller fixed-pad bearings with special reference to wear and very low speeds.

The results have been analysed to show the relative economy of the three types and how their performance characteristics influence the selection of a suitable bearing for any given application. As examples :

(1) the use of the hydraulic bearing overcomes the difficulty of disposing of the heat generated near the centre of a machine by a heavily loaded thrust bearing, by transferring the losses by oil pumping to external ancillary equipment ;

(2) with fixed pad bearings the excessive friction and wear during starting under load may be obviated by combining a suitable degree of hydraulic action with the hydrodynamic design ;

(3) both fixed pad and tilting pad bearings may be operated satisfactorily with extremely low oil pressures, thus making them attractive when external oil systems and pumps have to be simple and cheap.

Means for appreciably improving the performance of the bearings were evolved in the course of testing, and the results suggest lines for further development.

DE GUERIN, D., and HALL, L. F., Research Department, D. Napier & Son Ltd. *Some characteristics of conventional tilting pad thrust bearings.* Institution of Mechanical Engineers, Conference on Lubrication and Wear, 1st-3rd October, 1957.

In the course of comparative tests on three types of plain thrust bearing described in the paper previously summarised, some of the results

obtained suggested the need for a more detailed exploration of the functioning of bearings with tilting pads of conventional design. Tests were conducted with various arrangements of pads and with central and offset pivots. Pressure plots over the faces of pads were also obtained.

It was found that the use of a central pivot, which is employed when operation in both directions of rotation must be provided for, results in a certain loss of performance as compared with the normal pivot position at 0·4 of the width from the trailing edge.

The load-carrying capacity of individual pads was also found to be adversely affected by their proximity to adjacent pads in the bearing.

A most important observation which had not been expected was that tilting pads of conventional design do not tilt, except possibly at the lowest loads. The hydrodynamic wedge is formed under the influence of thermal distortion and load deflection of the pad, and these are sufficient to modify the pressure distribution considerably and unfavourably. The accepted theory is therefore inadequate for calculating the pressure distribution, and a new approach is necessary for improved design.

SIMPSON, F. F., D.L.C., and RUSSELL, R. W., A.M.I.Mech.E., Research Department, D. Napier & Son Ltd. *Influence of magnetic fields and the passage of electrical currents on the deterioration of ball bearings.* Institution of Mechanical Engineers, Conference on Lubrication and Wear, 1st-3rd October, 1957.

From time to time the failure of individual rolling-bearings in electrical machinery is ascribed to some form of electrical phenomenon. As factual evidence of the effects of running these bearings in magnetic fields and with current passing through the rolling-elements is practically non-existent, a machine has been prepared in which the influence of these two conditions can be studied.

It was found that the application of a steady field had little effect until magnetic saturation was approached in the shaft on which the bearing was mounted ; ball and track surface deterioration then set in and the life was reduced by a factor of nearly 10. A rise in operating temperature was observed but was shown not to be the cause of the reduction in life.

The passage of direct currents through the bearing produced softening of the track surfaces and pitting of the balls, the nature and extent of which depended on the magnitude of the current, and on the lubricant. Some form of damage to balls or tracks, or both, occurred in a short time at all values of current employed between $\frac{1}{8}$ amp and 50 amp.

BLOUNT, E. A., A.M.I.Mech.E., and DE GUERIN, D., Research Department, D. Napier & Son Ltd. *The importance of surface finish, loaded area conformity and operating temperature in small-end plain bearings for high duty two-stroke engines.* Institution of Mechanical Engineers, Conference on Lubrication and Wear, 1st-3rd October, 1957.

The operating conditions of a small-end bearing in a two-stroke engine have been simulated in a test machine, except that the relationship between the peak value of the load and the duration of loading is fixed. The effects upon a typical small-end bearing of loaded area conformity, of the degree of pin surface finish and of ambient temperature variation have been investigated.

The characteristic curve relating bearing temperature to peak load shows a sharp rise as the limiting load is approached, and this is used as the criterion in the load capacity tests.

It was found that, in general, improved conformity and better surface finish increased the load capacity, while elevated temperature reduced it. These effects were interrelated. For example, improvement resulting from better conformity, and deterioration due to elevated temperature, were found to be greatest when the pin surface was relatively rough. The advantage of good pin finish was greatest when conformity was poor and when the temperature was high.

Under good conditions of conformity and surface finish a peak load of 19,300 lb/in^2 was carried at an operating temperature of 127°C. Satisfactory methods were evolved for obtaining the desired degree of conformity.

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